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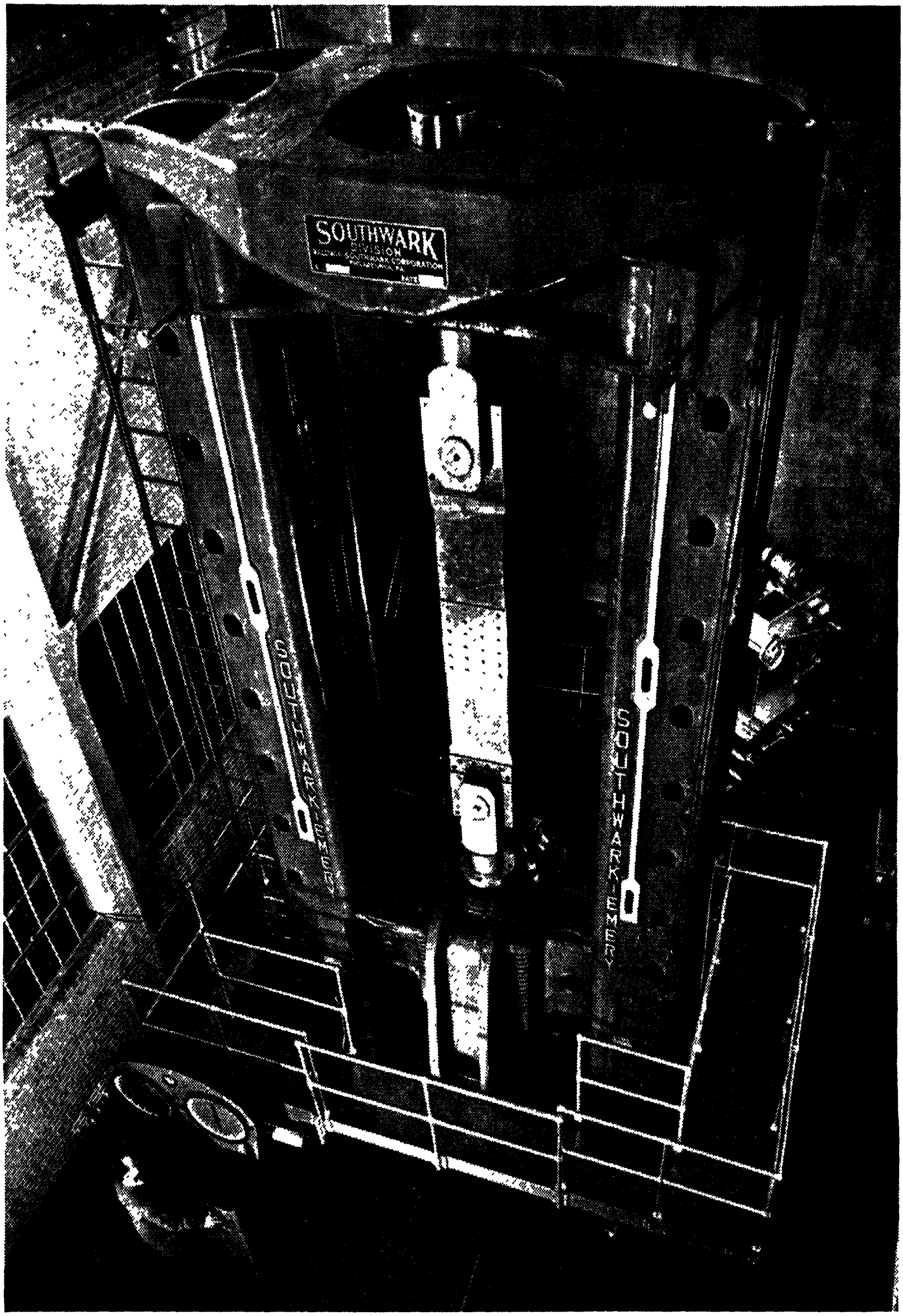

Riveted joint undergoing tension test in 3,000,000-lb. Southwark-Tate-Emery testing machine (called the "Templin Tester"). This, the world's most powerful testing machine, is installed in the Research Laboratories of the Aluminum Company of America. (Courtesy Aluminum Company of America)

Testing of
Engineering Materials

By

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PREFACE

TO THE STUDENT

It is the intent of the materials testing laboratory course to enable you to acquire a complete understanding of the physical properties of those materials commonly employed in engineering design, their application based on such properties, and their limitations. Introductory material is provided with each experiment to acquaint you with the principal problem of the experiment as well as to give supplementary information helpful in interpreting the test results you obtain.

Few of you who take the materials testing course will become testing engineers but many of you will at one time or another in your career have to formulate tests and interpret test results. In this text the applications of experimental results have been emphasized, whereas the technique of testing and detailed descriptions of test procedures have been minimized, except in those instances where they are of most importance.

TO THE INSTRUCTOR

A materials testing text should, through the conduct of an experiment and the questions included with it, rather than by mere statement, effectively convey to the student the purpose of an experiment. Every effort has been made to carry out this concept. The introductory chapter and similar material preceding each experiment are carefully correlated with the experiments; cross references are given when the theory is amplified and substantiated by actual experimental results. References to testing equipment are such that the text is adaptable to any type of apparatus.

This book is designed for a one-semester course. It is not anticipated that any one course can, or should, include all of the experiments in the book. However, a sufficient number is offered to render the text adaptable to specialized materials testing courses that might be made available to civil, mechanical or electrical engineers. The experiments need not be conducted in the suggested numerical order. There is only one experiment on concrete because in many curricula a separate and complete course is given in this subject.

The experiments may be completed in detail and submitted for grade, or the questions may be used as a guide by the student in studying the experiment and preparing for regular examinations given throughout the semester.

The mechanical work which the student customarily performs in setting up data sheets, curve sheets, and tabular forms for presentation of data has been reduced to a minimum so that more time may be devoted to experimental work. If mimeographed data sheets of the form suggested in the experiments are supplied to the students, a further saving of time may be effected.

The author wishes to thank the manufacturers and users of various types of testing machines for permission to use photographs of their equipment. The author will be grateful to users of this book who report to him any errors which might be discovered.

C. W. M.

Pittsburgh, Pennsylvania
January, 1944

CONTENTS

I. Testing of Engineering Materials 1- 22

II. Conducting Laboratory Experiments and Instructions for Writing Reports 23- 26

III. Experiments

1. TESTING MACHINES—THEIR USE AND CALIBRATION . 27- 47
2. THE STRESS-STRAIN DIAGRAM FOR MILD STEEL . . 48- 63
3. THE EFFECT OF CARBON CONTENT UPON THE PROPERTIES OF STEEL 64- 69
4. SHEAR, TENSION, COMPRESSION, AND COLD-BEND TESTS OF METALS 70- 76
5. FLEXURAL TEST OF A WOOD BEAM 77- 87
6. TORSION TESTS OF DUCTILE AND BRITTLE MATERIALS . 88- 97
7. IMPACT TESTS OF DUCTILE AND BRITTLE MATERIALS . 98-107
8. THE PROPERTIES OF GRAY, WHITE, AND MALLEABLE IRON 108-113
9. TENSION TEST OF NON-FERROUS METALS 114-118
10. THE PHYSICAL PROPERTIES OF LAMINATED PLASTICS . 119-124
11. HARDNESS TESTING 125-137
12. THE PHYSICAL PROPERTIES OF CONCRETE 138-149
13. COLUMN TESTS 150-155
14. STRAIN GAGES AND THEIR USE 156-172
15. TENSION, COMPRESSION AND SHEAR TESTS OF WOOD . 173-178
16. EFFECT OF MOISTURE UPON THE FLEXURAL PROPERTIES OF WOOD 179-181
17. TEST OF A HELICAL SPRING 182-185
18. FLEXURAL TESTS OF DUCTILE AND BRITTLE MATERIALS 186-188

Appendix

TABLE OF CROSS-SECTIONAL AREAS FOR ROUND SPECIMENS . 189-192

PERCENTAGE REDUCTION OF AREA TABLES 193-195

Index 197-200

PART ONE

TESTING OF ENGINEERING MATERIALS

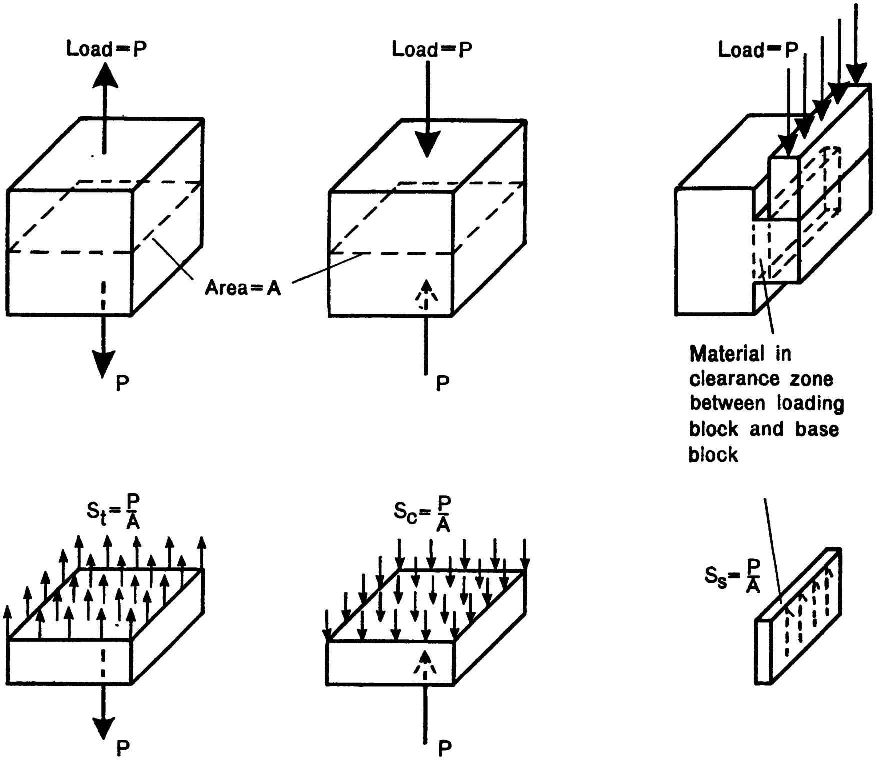
Each engineering material has certain inherent physical characteristics and properties, some alterable, some not, which make it more effective in performing some task which the designer contemplates. These properties may include such considerations as strength, color, weight, and thermal characteristics. Most engineers are interested in some form of the first consideration, strength. The architect is interested in the first two, the airplane designer in strength and weight, and the heating engineer in strength and thermal characteristics. The strength considerations are therefore of more general interest, whereas the other properties mentioned may be considered as special cases and will not be discussed in this text.

Engineers are too prone to adopt the attitude of the non-engineering or non-technical man and consider the term strength as some abstract property by which a material may or may not be able to qualify for some particular use. Many practicing engineers, today, still consider the various properties of engineering materials to be summed up in the breaking strength of that material, as determined by the ordinary short-time, room-temperature test. It is the purpose of this book to present to the engineering student, through comprehensive testing of a wide variety of materials and a careful analysis of their test results, a clear picture of those properties which can most readily be illustrated in the testing laboratory and in the time usually available. The acquisition of a real understanding and "feel" for the common engineering materials and their limitations, as governed by properties other than the static breaking strength, is a valuable asset to any engineering designer. As the various experiments are conducted and the data therefrom are carefully studied and analyzed, it will become more and more apparent that the static ultimate strength of most materials is the most unused property in engineering design.

Stress.—The three forms of stress recognized in engineering design are *tension, compression,* and *shear.* See Figure 1. Seldom, if ever, do stresses exist singly; usually they are present in combination. To provide the designer with quantitative values of strength, stresses are reported as unit values, the unit being the square inch. The relationship between stress, load, and area supporting that load is expressed as follows:

$$P = As \quad \text{or} \quad s = \frac{P}{A} \qquad (1)$$

in which s = the unit tensile, compressive, or shearing stress in pounds per square inch, usually written as lb. per sq. in. or psi.
P = total applied load in pounds.
A = cross-sectional area in square inches.



(a) Tension (b) Compression (c) Shear

FIG. 1. The three forms of stress.

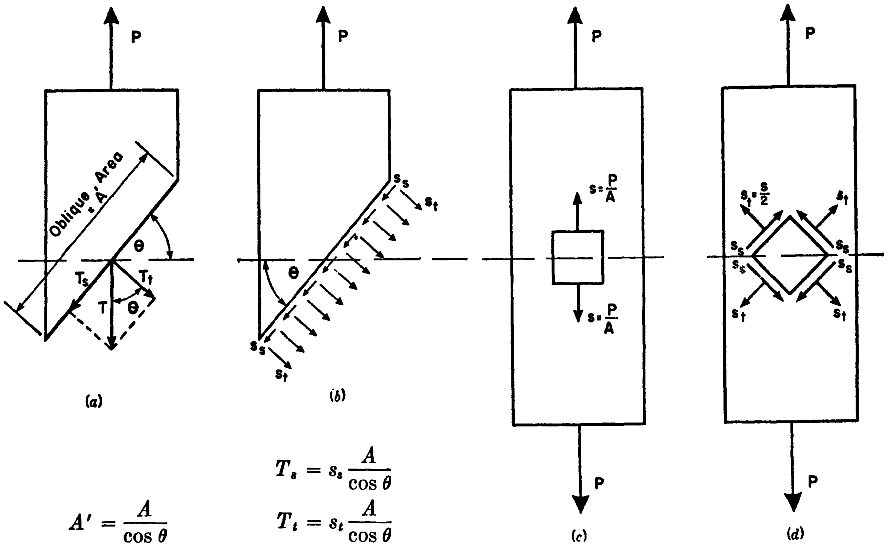
Although the term unit stress is the correct terminology for s, it is commonly referred to simply as stress. The tensile stress may be designated by s_t, the compressive stress by s_c, and the shearing stress by s_s.

It should be realized that the laboratory tension test, intended only to determine the tensile properties of a material, produces a combination of both tension and shear while the compression test produces a combination of compression and shear. This fact may be seen by passing an oblique plane through the centroid of the cross-sectional area of the block shown in Figure 1(a). The sum of the unit stresses on the transverse face may be represented by T, so that

$$T = s_t A = P.$$

Then the sum of the unit stresses on the oblique plane shown in Figure 2(a) must also equal T for equilibrium. The component T_s is the sum of the shearing stresses along the plane. The component T_t is the sum of the tensile stresses normal to the plane. The oblique area, A', will be

$$A' = \frac{A}{\cos\theta}.$$



$A' = \frac{A}{\cos\theta}$ Forces on oblique plane

$T_s = s_s\frac{A}{\cos\theta}$ $T_t = s_t\frac{A}{\cos\theta}$ Unit stresses on oblique plane

Maximum unit tensile stress

Maximum unit shearing stress

FIG. 2. Determination of forces on an oblique plane.

Assuming the shearing and tensile stresses to be constant over this area they may be summed as follows:

$$T_s = s_s\frac{A}{\cos\theta} \quad \text{and} \quad T_t = s_t\frac{A}{\cos\theta}$$

but since

$$T_s = T\sin\theta, \quad T_t = T\cos\theta, \quad \text{and} \quad T = P$$

they may be written

$$T_s = P\sin\theta = s_s\frac{A}{\cos\theta}$$

and

$$T_t = P\cos\theta = s_t\frac{A}{\cos\theta}.$$

Solving for the unit stresses in each case gives

$$s_s = \frac{P}{A}(\sin\theta\cos\theta) = \frac{P}{2A}\sin 2\theta \tag{2}$$

$$s_t = \frac{P}{A}\cos^2\theta. \tag{3}$$

It may be seen from Equations (2) and (3) that the maximum shearing stress on an oblique section will occur when $\theta = 45°$ and, that for this condition, s_s will be $0.5s_t$. Thus the shearing and normal stresses on a 45° plane in an axially loaded specimen are equal to each other and to one half of the axial stress. Obviously s_t will be a maximum on a transverse section ($\theta = 0$). Equations (2) and (3) are helpful in interpreting strain gage data, as will be discussed in Experiment 14.

[If the shearing strength of a material is less than one half of the tensile or compressive strength, failure at rupture in most cases will be governed by the shearing strength even though the material is loaded in tension or compression.]

Strain or Distortion Resulting from Load.—Any material when subjected to load is distorted by lengthening, shortening, or twisting, depending upon the type of load. Thus the blocks of Figure 1 will be stretched in tension and shortened in compression. This change in linear dimension is referred to as *strain.* The unit strain or unit deformation for tensile or compressive loads may be found from the relationship

$$\epsilon = \frac{e}{L} \tag{4}$$

in which ϵ = unit strain or deformation in inches per inch.
e = total lengthening or shortening under load in inches.
L = length in inches over which e is measured.

The shearing strain involves the relative movement of parallel planes. In Figure 3 is shown the small amount of material representing the clearance between the loading and supporting block of the specimen in Figure 1(c). As shown in Figure 3 the distortion due to shear will permit this rectangular section to assume a rhomboidal shape. For the thickness t the unit strain in shear will be

$$\epsilon_s = \frac{e_s}{t}$$

in which ϵ_s = unit shearing strain in inches per inch.
e_s = total shearing deformation in inches.
t = thickness in inches of distorted section,

which is also equal to the tangent of the angle of inclination. Since for the small angles of inclination or twist encountered in elastic shear the tangent of the angle and the angle, as measured in radians, may be assumed equal, the above expression may be written

$$\epsilon_s = \frac{e_s}{t} = \alpha \tag{5}$$

in which α = angle of inclination or distortion in radians.

In an effort to give a better understanding of materials under load, the units for strain have not been reduced dimensionally but have been left as a deformation in inches per inch. These units give a better physical concept of the dimensional evidence of strain resulting from the application of force. The term unit strain is often referred to simply as strain.

The student should realize that the theoretical relationships presented in this chapter assume a perfectly uniform material and uniform distribution of load. This condition rarely, if ever, exists even in the most carefully prepared and tested laboratory specimens. These formulas are, therefore, more properly referred to as "statistical" formulas, indicating that on the average the actual stress or strain will be equal to the calculated value.

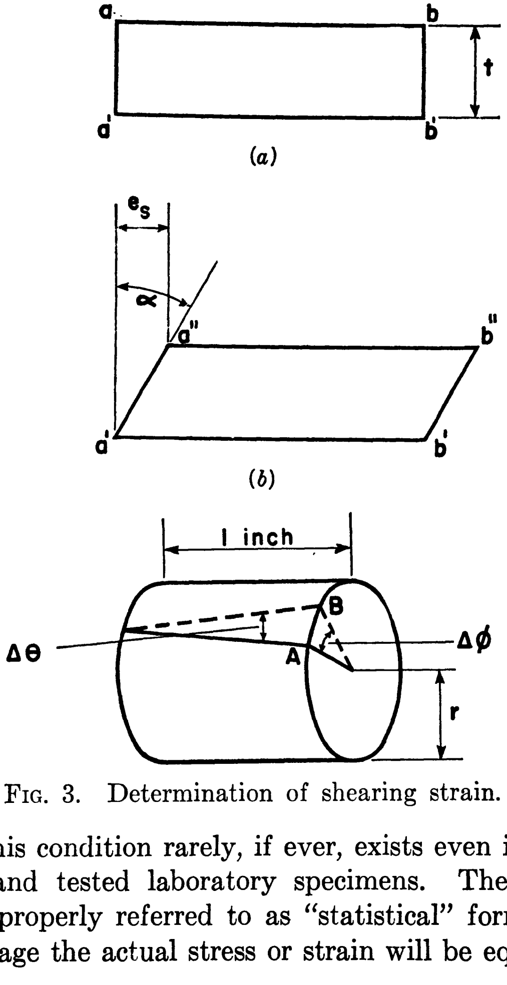


FIG. 3. Determination of shearing strain.

Stress-Strain Diagram.—The experimental relationship between stress and strain, as determined by the tension or compression test, may be reported graphically in the form of a stress-strain diagram. Portions of some characteristic stress-strain diagrams or curves are shown in Figure 4. These curves show that some materials have an elastic range followed by a plastic range, while others are only elastic or entirely plastic. Important design properties as well as a physical concept of a material's response to load may be obtained from such diagrams, as will be shown in Experiment 2.

Poisson's Ratio.—The longitudinal elastic strain produced by a tensile or compressive load causes a transverse deformation due to the reduction in cross-sectional area. The ratio of the transverse deformation of a unit of material to the longitudinal deformation is called *Poisson's ratio.* Referring to Figure 5 the ratio may be expressed as

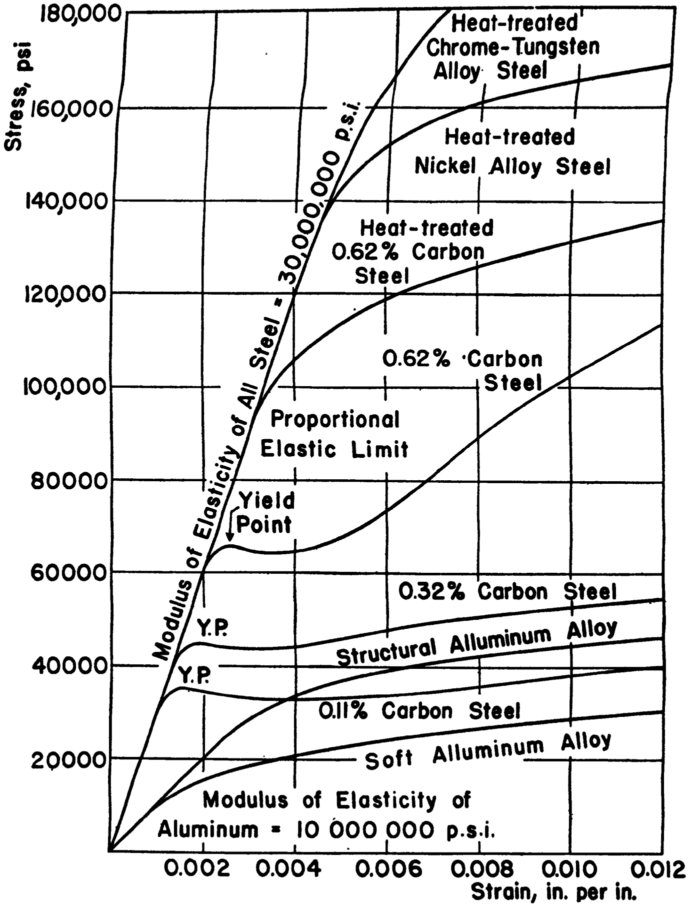


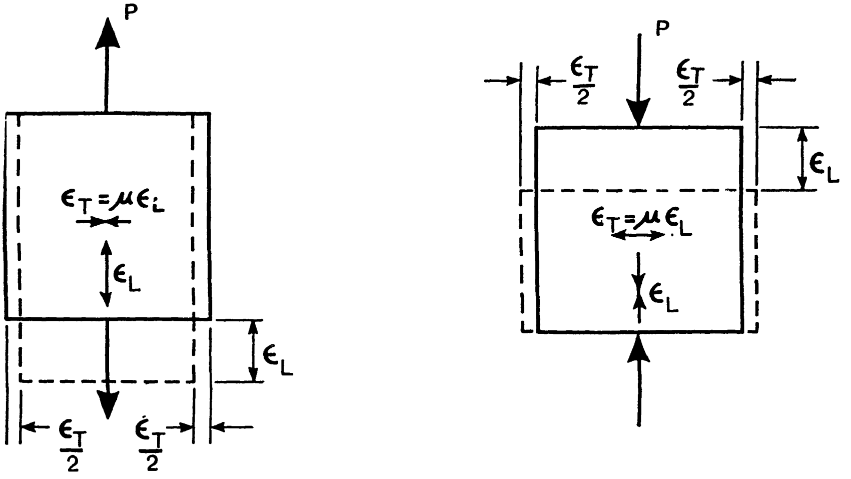
FIG. 4. Stress-strain diagrams for various metals. Note that the modulus of elasticity of all steels is the same, regardless of the tensile strength of the steel. The same is true of aluminum.

$$\mu = \frac{\epsilon_T}{\epsilon_L} \qquad (6)$$

in which μ = Poisson's ratio.
ϵ_T = transverse strain, in. per in.
ϵ_L = longitudinal strain, in. per in.

From Figure 5 it may be seen that a tensile load causes a transverse compressive strain and a compressive load causes a transverse tensile strain. Poisson's ratio is helpful in analyzing the deformations in a material subjected to something other than unidirectional stresses.

True Stress-Strain Diagram.—The values of stress plotted in the ordinary stress-strain diagram are obtained by dividing each increment of load by the original cross-sectional area of the specimen. It has been shown, however, that the cross-sectional area of a specimen subjected to axial load is changed due to transverse strain. Because of this change in cross-sectional area the values of stress should be modified as governed by the correct areas. When the load applied to a specimen is divided by the actual cross-sectional area obtained from the diameter measured at that load, a stress, referred to as the *true* stress, is obtained. These values of true stress may be plotted against the measured strains to give the true stress-strain diagram. This diagram is helpful in determining the total energy expended in fracturing a specimen or in plastically working it a certain amount, and will be discussed in greater detail in Experiments 2 and 7.



Tension Compression

FIG. 5. Relationship of longitudinal to transverse strain in determining Poisson's ratio.

The tensile strength of a material is obtained by dividing the ultimate load by the original cross-sectional area. Since the area is reduced due to the transverse strain, the value obtained for tensile strength in this way is in error, but on the safe side. For mild steel the error is about 20 per cent; for structural aluminum 14 per cent; and for soft copper 40 per cent.

Modulus of Elasticity.—Within certain limits, most materials exhibit a proportionality of stress to strain as shown in Figure 4. This relationship is called *Hooke's law.* Although experiments yield data which give this straight-line relationship for many materials, it is doubtful if the structure of metals is such that the relationship holds throughout the test specimen. Some metals, particularly cast iron, and non-metallic materials, such as wood and concrete, show little or no proportionality of stress to strain because of their lack of homogeneity. In most cases it may be assumed, however, as is done here, that the straight-line relationship between stress and strain when observed experimentally on relatively large specimens is correct for all parts of the specimen.

The quantitative measure of the proportionality of stress to strain is called *Young's Modulus* or the *modulus of elasticity.* In equation form it may be stated as

$$E = \frac{s}{\epsilon} \tag{7}$$

in which E = modulus of elasticity, psi.
s = stress, psi.
ϵ = strain, in. per in.

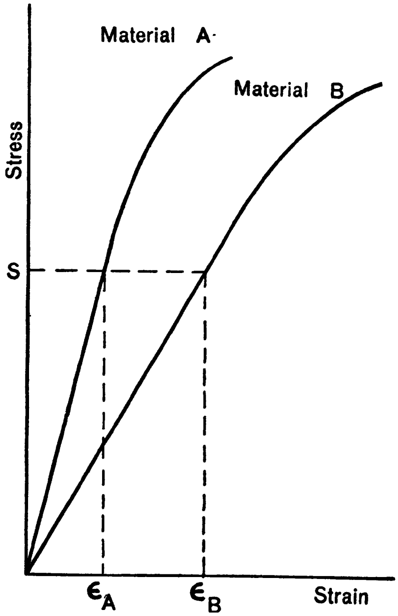


FIG. 6. How modulus of elasticity measures stiffness. Material A is stiffer than material B since ϵ_A is less than ϵ_B.

Since this property may be determined as the slope of the straight-line portion of the stress-strain diagram it is obvious that a material having a high modulus of elasticity will not lengthen, shorten, or bend as much under load as a material having a lower modulus. The material with the greatest modulus of elasticity is then said to be the stiffer of the two. The modulus of elasticity is, therefore, a measure of the stiffness of a material and is one of the most important physical properties. The modulus of elasticity of a material is independent of its ultimate strength, a fact too often forgotten by designers, and varies but little for any one metal, as, for example, steel. As may be seen from Figure 4, the modulus of elasticity of most steels is approximately 30,000,000 lb. per sq. in. and that of aluminum about 10,000,000 lb. per sq. in., regardless of the ultimate strength. This property is seldom affected appreciably by heat-treatment, cold- or hot-working, or mild alloying.

The practical application of the modulus of elasticity may be illustrated by Figure 6. Cubes having 1-inch sides are made of the materials designated as *A* and *B*. Material *A* has the steeper slope of the straight-line portion of the stress-strain diagram and therefore has the higher modulus of elasticity. When the cubes are subjected to a compressive total load which produces a unit stress *s*, they shorten in proportion to their moduli of elasticity, as may be found from Equation (7). Since material *A* is the stiffer, as shown by the fact that the strain ϵ_A is less than ϵ_B, this cube shortens the smaller amount.

Shearing Modulus of Elasticity; Modulus of Rigidity.—To determine the deformation of a material subjected to shearing loads, whether the load causes only shear or combinations of shear and tension, as in torsion, it is necessary to know the material's modulus of elasticity in shear. This property is often referred to as the modulus of rigidity and is usually determined experimentally from the torsion test. In Figure 3(c) is shown a 1-inch length of shaft subjected to a twisting load which produces shear across the transverse face. The shearing strain resulting from the load is represented by *AB*. If s_s is the shearing stress caused by the load, then

$$G = \frac{s_s}{r\Delta\phi} \tag{8a}$$

in which G = modulus of rigidity, lb. per sq. in.
s_s = shearing stress, lb. per sq. in. For the relationship which determines s_s see Experiment 6.
$\Delta\phi$ = angular twist of a transverse section about the longitudinal axis, radians.
r = radius of shaft, in.

Or, since

$$(1)\Delta\theta = r\Delta\phi$$

Equation (8a) may be written

$$G = \frac{s_s}{\Delta\theta} \tag{8b}$$

in which G and s_s are as given above.
$\Delta\theta$ = longitudinal twist of shaft, radians per inch of length.

The modulus of elasticity in shear is seldom reported and it is therefore of interest to know that it may be determined from the modulus of elasticity in tension or compression from the relationship

$$G = \frac{E}{2(1 + \mu)} \tag{9}$$

in which G = modulus of elasticity in shear, psi. (modulus of rigidity).
E = modulus of elasticity in tension or compression, psi.
μ = Poisson's ratio.

Proportional Elastic Limit.—Most materials are not elastic over their entire loading range. The limit of the proportional relationship between stress and strain is appropriately called the *proportional limit.* It is possible that a test specimen of some material may be loaded beyond this point and yet return to its original length or shape. This condition is determined experimentally by loading a test specimen with increasingly larger increments and returning to some small original load after each increment, noting the reading of the extensometer attached to the specimen each time the load is released. When the extensometer shows that the material is no longer returning to its original length, the so-called elastic limit has been reached. For most materials this point is only slightly beyond the proportional limit and is usually considered to be the same. Obviously the extensometer used to determine the elastic limit should be both accurate and sensitive to small amounts of strain. No doubt many values for elastic limit have been secured with instruments having some backlash which permitted them to return to an original value even though some permanent deformation had actually taken place. Because of the questionable testing procedure often used to determine the elastic limit and, since the value obtained is seldom very much beyond the proportional limit, these two properties will be combined in this text and the term *proportional elastic limit* will be used to designate the limit of elastic action.

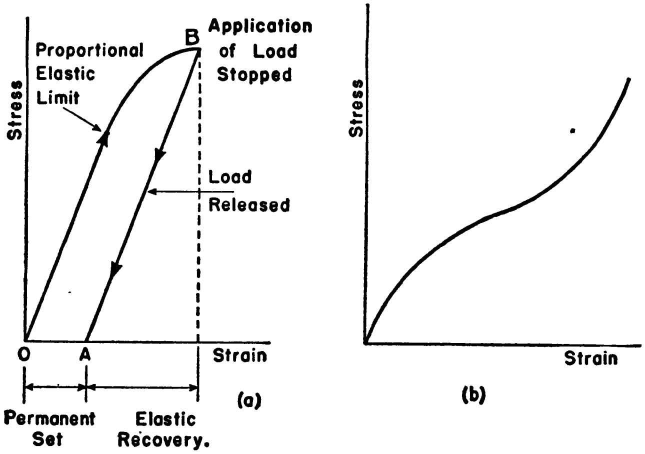


FIG. 7. Stress-strain diagrams showing limit of elastic action, permanent set resulting from application of load beyond the proportional elastic limit, and elasticity in a material (b) when stress is not proportional to strain.

A material need not have a straight stress-strain diagram to be considered elastic. Any material which, upon release of the load imposed upon it, will return to its original length and shape may be called elastic. Thus, in Figure 7(a), the material will be perfectly elastic if the unit stress does not exceed that at the proportional elastic limit but, when the stress exceeds this value, the permanent deformation *OA* results.

In Figure 7(b) is shown the first portion of a stress-strain diagram for one type of rubber. This is certainly not a straight-line relationship but the material may be considered elastic if it exhibits no permanent deformation or "set" when the load is released.

Johnson's Apparent Elastic Limit.—A term occasionally used to supplant that of elastic limit is Johnson's *apparent elastic limit.* The application of this method is shown in Figure 8. Through the origin a straight line is drawn having a slope 50 per cent greater than the straight portion of the stress-strain diagram. A supplementary line is then drawn parallel to this line, as shown in Figure 8, and the point of tangency of this supplementary line and the knee of the diagram is the apparent elastic limit. This method is not so directly dependent upon scale of plotting or personal interpretation of the stress-strain diagram as is the proportional elastic limit. For design purposes, however, the latter value may safely vary by more than the error with which it can readily be determined. Since an exact value for limit of elastic action is seldom of more than academic interest, the more easily determined proportional elastic limit will be used here. Johnson's apparent elastic limit may also be found, however, by using the outline above.

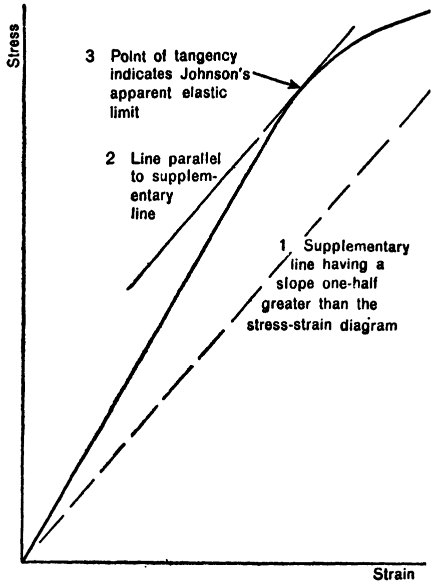

Stress
3 Point of tangency indicates Johnson's apparent elastic limit
2 Line parallel to supplementary line
1 Supplementary line having a slope one-half greater than the stress-strain diagram
Strain

Fig. 8. Determination of Johnson's apparent elastic limit.

Tangent Modulus.—Beyond the proportional elastic limit the material does not lose its stiffness but rather has a constantly decreasing stiffness. The modulus of elasticity at any stress may be determined by drawing a line tangent to the stress-strain diagram at that point and calculating the slope of this tangent. The value obtained is called the *tangent modulus of elasticity.* A characteristic tangent modulus curve for a low carbon steel is shown in Figure 9. This type of curve and the tangent modulus in general have some applications in metal working problems.

Yield Point.—As the load on a mild steel specimen is increased beyond the proportional elastic limit a region of extreme plastic deformation is reached. This is the yield region and its two limiting points are called *yield points.* The upper yield point, the more important value in commercial testing, which is usually referred to simply as the yield point, is observed as that condition of stress during a test where there is a considerable increase in strain without a corresponding increase in stress. The lower yield point indicates the limiting position of the severe plastic deformation induced by the internal action of the structure of the metal at the upper yield point.* The term yield point is a misnomer since the material has actually started to yield at the proportional elastic limit. It might more properly be called the "rapid yield point."

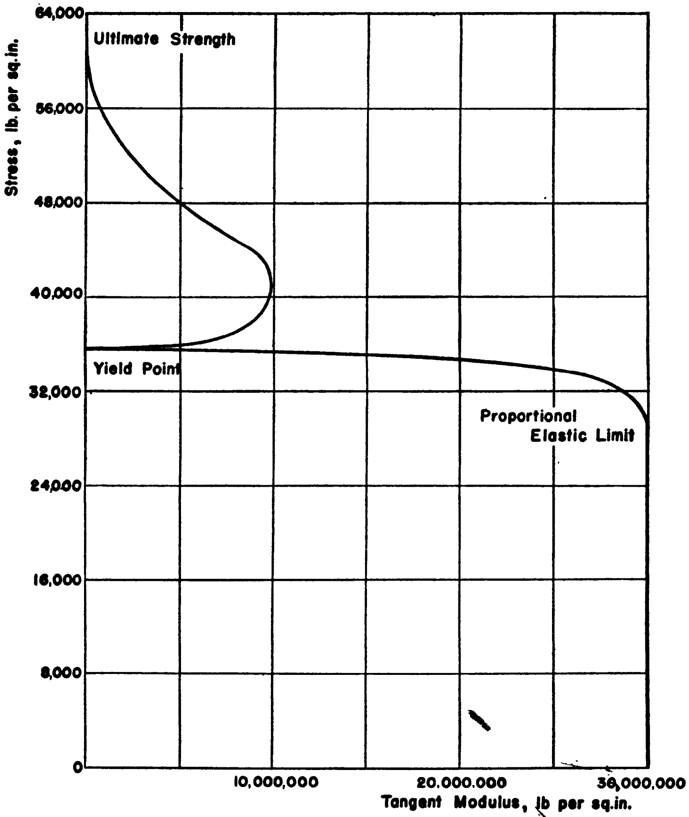


FIG. 9. Characteristic stress-tangent modulus curve for mild steel.

Only a few of the materials of engineering exhibit the phenomenon of sudden yielding. Because of the wide use of the mild structural steels, which have a yield point, many engineers have come to regard this property as a desirable one and are at a loss to decide on design considerations for a material which has no yield point. The yield point has considerable design value when the permanent deformation at this point is not so large that it might cause excessive distortion if the structure should be loaded to this value. Since the permanent set at the yield point is usually small, this property may safely be used for limiting stresses in most structural design, except when elastic buckling is to be considered.

---

* It should be pointed out that the lower yield point is the value which is most consistently reproduced in tests. The upper yield point can be varied by changing the specimen dimensions. In metal forming operations and in metal working problems the upper value can usually be ignored.

The yield point may be determined experimentally in three ways, the most accurate of which is the drop of the beam method.* When a specimen is loaded in a testing machine, the increase of load will be almost constant up to the yield range. At this point, the very sudden increase in strain will cause the specimen to stretch under the previously applied load faster than the load can be applied. The load therefore drops off and the stress at the yield point is obtained from the load observed just before the weighing system indicated a decrease in load. An alternate method is by the use of dividers which are placed in two punch marks along the specimen before loading starts. When the yield point is reached the dividers will suddenly no longer fit into the two punched holes. Although this method is not as accurate as the first one, it is often used when the yield point is rather obscure and the drop of the beam may be difficult to detect. The least desirable method is the fall of the mill-scale. This method of determining the yield point may only be used for hot-rolled steels having the characteristic oxide coating called *mill-scale.* The steel of the bar is relatively soft and has a yield point, while the mill-scale has none; therefore when the yield point is reached the brittle scale will flake off and give an indication of the yielding action.

Yield Strength.—For those materials which do not exhibit the phenomenon of sudden yielding, and most engineering materials fall in this category, it is necessary to substitute some other property for the yield point. When a metal has no yield point, the stress-strain relationship gives a smooth curve beyond the proportional elastic limit. Non-metallic materials, non-ferrous metals, and alloy steels have this type of diagram. See Figure 4. The yield strength forms a satisfactory substitute for the yield point when it is realized that a material has already begun to yield before the so-called yield point has been reached. Thus, in Figure 7(a), if the point where the loading is stopped is the yield point, the release of load will result in permanent set as previously explained. If there had been no yield point and the curve had continued smoothly beyond this point the procedure could have been reversed to determine the point *B*, which is called the yield strength. The yield strength is then defined as the stress necessary to produce a limiting value of permanent set. The value for the permanent set is expressed as a percentage of the original gage length. The offset, or limiting value of permanent set, may vary from 0.01 per cent (for "proof stress" for ordnance materials) to 0.35 per cent for some bronzes. Detailed values are given in Experiment 9 on

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* With testing machines having a self-indicating type of dial employing a pointer and circular face, the yield point may be observed by the "fall of the pointer." That is, the pointer drops back to indicate that the load has decreased.

Non-Ferrous Metals. A general specification for determining yield strength would be as follows:

Yield strength (0.2 per cent permanent set) = 44,000 psi.

and it would be obtained from the stress-strain diagram for the material as shown in Figure 7(a). The permanent set of 0.2 per cent should be interpreted as each inch being deformed 0.002 inch per inch. This value of set is then laid off along the abscissa and a line is drawn through this point parallel to the initial straight-line portion of the curve. Its intersection with the curve at *B* is the yield strength.

To determine the yield strength satisfactorily requires a stress-strain diagram obtained with an extensometer reading to 0.0001 inch per inch of gage length. With this type of extensometer attached to the specimen the load may be applied and released in small increments beyond the proportional elastic limit until the specified set is observed. The terms yield point and yield strength are often confused and interchanged. They may even be erroneously introduced into specifications as, for example, when a designer requires a certain minimum yield point for a material that actually has no yield point. Inasmuch as the yield point often gives evidence of a material that is very ductile it should not be applied to materials having a smooth stress-strain diagram. Conversely it is not necessary to determine the yield strength of a material having a yield point unless otherwise specified.

Ultimate Strength.—The maximum load which a specimen under test will hold is used to determine the strength of the material. This load when divided by the original cross-sectional area gives the ultimate strength or the material's ability to resist fracture under static loading. The actual stress at the ultimate load is larger than that calculated by this method since the original area has been reduced due to the longitudinal plastic distortion. This method gives results on the safe side, however, and is ordinarily used in routine testing work.

As indicated previously the ultimate strength of a ductile material is one of the least desirable of its physical properties. It is, however, of importance in designs using brittle materials, as will be seen in Experiments 6, 8, 10, 12, and 18.

The maximum usable strength of a material subjected to static loading may be taken as either the proportional elastic limit or as the yield point or yield strength. The choice of any one of these properties will depend upon the use of the material. Thus it may be reasonable to use the yield point or yield strength as a criterion for the design of structural parts where small distortion will be of no consequence. A valve spring, however, will be loaded elastically and the stress at the proportional elastic limit will govern the design.

The ultimate strength of a ductile material in compression is taken as one of the yield values or as the proportional elastic limit. A small specimen of ductile material loaded in compression will continue to take load far beyond the yield point, but the part will be so severely distorted that it can no longer be considered usable.

Ductility.—A material which has the ability to stretch out or deform inelastically under load is said to be *ductile.* Brittleness is the opposite of ductility and indicates that the material will fracture with little permanent distortion. Ductility is an important property of materials which are to be formed and bent to shape, such as tanks, automobile bodies, cartridge cases, and other drawn or stamped metal parts.

In a tension test the ductility of a material is obtained from the elongation and from the reduction in area, both being expressed as a percentage. The elongation is $e_f - e_0$ and the percentage elongation is

$$\frac{e_f - e_0}{e_0} \times 100 \qquad (10)$$

in which e_0 = original length of specimen over that portion subjected to approximately uniform load, in.
e_f = final length of the same length defined by e_0, in.

The reduction in area is $A_0 - A_f$ and the percentage reduction in area is

$$\frac{A_0 - A_f}{A_0} \times 100 \qquad (11)$$

in which A_0 = original cross-sectional area of specimen in that portion subjected to approximately uniform load, sq. in.
A_f = final cross-sectional area at the reduced portion of the fractured specimen, sq. in.

Since the elongation is a function of the length over which it is measured it is important that this length, called the *gage length,* be stated when values for elongation are reported. The correct way to specify this property is, for example,

Elongation (2-inch gage length) = 36 per cent, or
Elongation in 2 inches = 36 per cent.

That a statement of the gage length is important may be seen from Figure 10. Thus the elongation for the 0.15 per cent carbon steel, as can be seen from this figure, could be reported as between 24 per cent and 58 per cent. Either value would be meaningless, however, unless the length over which it was obtained was also reported.

Malleability is a special case of ductility which qualitatively indicates a material's ability to be hammered and worked, particularly into thin sections or sheets.

The ductility of a material used in structural design is of more importance than is commonly realized. Localized inelastic action, which is possible only with ductile metals, permits a riveted or welded structure to give slightly under load and to adjust itself to the normal errors of constructional workmanship. Brittle materials cannot make this adjustment by local yielding so that high stresses are encountered and failure often results even though the statistical design formulas predicted low average stresses.

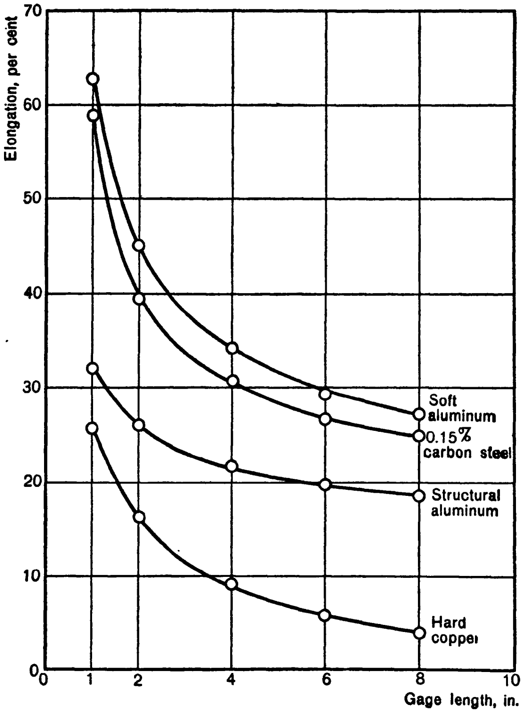
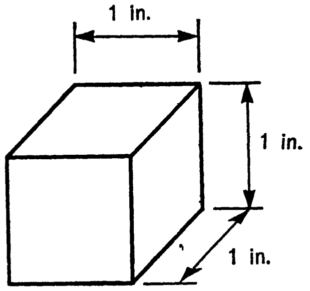


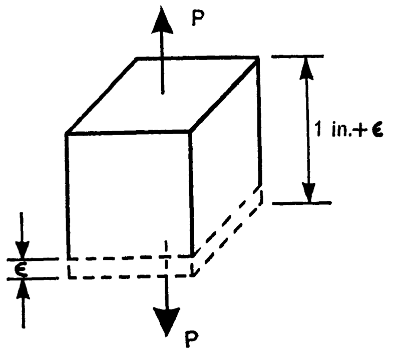
FIG. 10. Variation in percentage elongation with gage length, showing that elongation is a function of gage length.

Fracture Toughness.—When high strength and ductility are combined they measure the property of fracture toughness. Since strength, or stress, and ductility, or elongation, are both found in the stress-strain diagram, the area under this diagram may be taken as a measure of the toughness of a material. The ability to absorb fracture energy (force × distance) is expressed quantitatively by the *fracture toughness.* It can be seen from a study of their stress-strain diagrams which of two materials is the tougher. For extremely ductile materials the ordinary stress-strain diagram will not give a correct measure of fracture energy. For such materials it is necessary to use the "true" stress-strain diagram as has been explained previously and as will be done in Experiments 2 and 7. Some materials are strong but not tough, whereas others are tough but not strong. A comparative measure of fracture toughness may also be obtained from the impact test.

Elastic Toughness; the Modulus of Elastic Resilience.—Elastic toughness is found in a material which can absorb considerable energy without being permanently deformed. In Figure 11 is shown a unit cube of a homogeneous material 1 inch long and having 1 square inch of cross-sectional area under no load. At a load of P pounds the block has stretched the amount ϵ inches. The work is therefore



Zero load



After loading

FIG. 11. Unit cube of material elastically distorted by load P.. Determination of elastic resilience. Transverse deformation not shown.

$$\begin{aligned}\text{Work} &= \text{Average Force} \times \text{Distance}\\ &= \tfrac{1}{2}P\epsilon\end{aligned}$$

but inasmuch as $P = As$, the work may also be expressed

$$\text{Work} = \frac{As}{2}\,\epsilon.$$

Since the cross-sectional area, A, is 1 sq. in. and $\epsilon = s/E$

$$\text{Work} = \frac{s^2}{2E}\ \text{in.-lb. per cu. in.}$$

The work done is a measure of the energy expended, while the modulus of resilience is a quantitative measure of the energy which may be recovered. To find the work energy recoverable the relationship for modulus of resilience, E'_R, is written

$$E'_R = \frac{s^2}{2E} \text{ in.-lb. per cu. in.} \tag{12}$$

Equation 12 may be used to determine the modulus of resilience, or recoverable energy, at any stress. To determine the maximum energy which may be recovered without permanent set the stress at the proportional elastic limit should be used and the modulus of elastic resilience, E_R, thus obtained may then be written

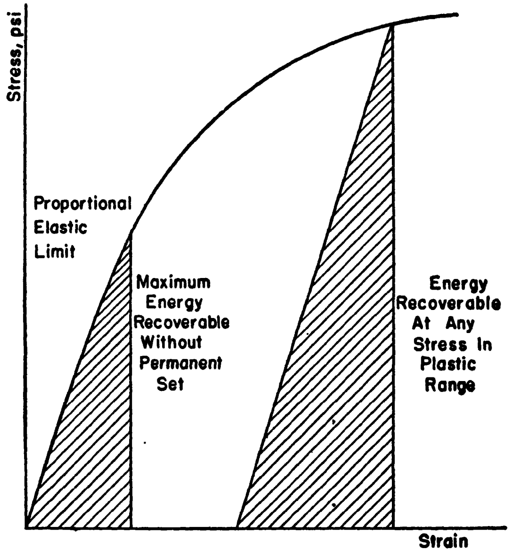


FIG. 12. Modulus of *elastic* resilience (*left*) and modulus of resilience (*right*) as obtained from the area under the stress-strain diagram.

$$E_R = \frac{(s_{pl.})^2}{2E} \text{ in.-lb. per cu. in.} \tag{13}$$

This valuable engineering tool may also be determined from the stress-strain diagram as shown in Figure 12. At the proportional elastic limit, or at any other point, the total area under the diagram is a measure of the expended energy, while the recoverable energy may be measured by the shaded triangular portion. In the latter case the area of the triangle will be ½($s\epsilon$), which may be simplified to give the relationships in Equations 12 or 13. The units for modulus of resilience may be reduced to pounds per square inch and are often reported that way. In this text, however, the property will be reported in terms of inch-pounds per cubic inch. These units are more expressive of the physical significance of the modulus of resilience, indicating that some number of inch-pounds of energy may be recovered from each cubic inch of the material. Thus a 1-in. cube of a material having a modulus of elastic resilience of 20 in.-lb. per cu. in. will momentarily be stressed to the proportional elastic limit when struck by a 1-lb. weight falling through 20 in.

The modulus of elastic resilience is very helpful in selecting material for leaf and coil springs, recoil mechanisms, airplane parts, and reciprocating machine parts. In all of these applications the material must absorb energy loads elastically to prevent distortion. For such use a material will often be selected on the basis of its modulus of elastic resilience. As may be seen from Equation 13 the modulus of elastic resilience, for a given proportional elastic limit, increases with a decreased modulus of elasticity. Thus some structural aluminum alloys have three times the ability of low carbon structural steel to absorb energy elastically.

Hysteresis.—When a material (particularly a metallic material) stressed in the plastic range is unloaded and then reloaded, the diagram thus formed does not consist of a single straight line but, rather, a loop made up of two slightly curving lines. This loop is referred to as a *hysteresis* loop and the area between the lines is a measure of the energy lost due to a cycle of unloading and loading. This energy is lost in the form of heat. The amount of energy lost depends upon the rate at which the load is removed and applied, as well as the kind of material. Hysteresis is important in materials such as rubber since it causes the material to rise in temperature and may thus affect other physical properties. A diagram showing the hysteresis effect can be obtained from the tensile stress-strain diagram, if the extensometer which is used has enough travel to permit measurements of strain to be obtained in the plastic range. In this text it is recommended that the hysteresis effect be shown in connection with the torsion test as will be done in Experiment 6.

Elastic Ratio.—A term which clearly expresses the loading range over which a material may be used, and yet be considered approximately elastic, is the *elastic ratio*. It may be expressed

$$R_E = \frac{\text{Stress at yield point or Yield strength}}{\text{Stress at ultimate}}(100) \qquad (14)$$

and is written as a percentage. The elastic ratio is not commonly reported in test data but it is useful because it permits a rapid comparison of materials for some usable, approximately elastic, loading range.

Hardness.—A qualitative determination of the hardness of a material may be obtained by measuring its resistance to indentation or scratching. While many tests are available for measuring hardness they are all comparative and only serve as a guide for the selection of materials to resist wear and abrasion and as a quick check test to control heat-treating operations. This property will be studied in detail in Experiment 11.

Types of Loading.—The manner in which load is applied to a structural member influences greatly the selection of the physical property which will govern its design. The three ways in which load may be applied are as follows:

1. Static loads are slowly applied to the part and remain reasonably constant in magnitude for the life of the structure. Most of the structural members of a building may be included in this group, especially if the so-called dead load is much larger than the added load caused by the use of the building (live load).

2. Energy or impact loads are suddenly applied forces which must be absorbed by the material. In some cases they may be resisted elastically (for example, an automobile leaf spring), in which case the modulus of elastic resilience will govern the design.

When distortion may be permitted (for example, a railroad car coupler), the fracture toughness will govern the design.

3. Repeated loads are found in the reciprocating parts of an internal combustion engine, a locomotive side rod, or a railroad car axle. In such applications the static strength of the material is of little importance since a member may fail suddenly and without warning, even though stressed in the normal design range by having such stresses repeated many, many times.

Creep, Fatigue, Wear, and Corrosion.—Tests for physical properties other than those included in this text are made in routine testing as well as research investigations. In general, time is not available in most engineering materials testing laboratory courses to conduct these additional tests. Should sufficient time be available, however, they may be set up as additional work. More complete information regarding any of these properties may be obtained from any Materials text. The important physical properties not included are briefly summarized in the following paragraphs.

Creep is the plastic and inelastic distortion of a material subjected to long-time loading. A load which produces a unit stress of less than the usual short-time static breaking strength may cause failure of the material in a few hours, a few days, or a few years. In some cases creep takes place at less than room temperature, as for lead; or slightly above room temperature, as for aluminum; or at very high temperature, as for alloy steel. Creep problems are encountered in the design of steam turbines, boilers, refinery equipment, and in other conditions where stress and improperly high temperatures are combined.

Internal discontinuities, such as cracks, foreign inclusions, or internal stresses resulting from heat-treating or like operations, will spread under repeated loading and cause sudden brittle-like failures even in ductile materials. This failure due to repeated loading is erroneously referred to as *fatigue* because of the appearance of the broken section which consists

DUCTILE MATERIALS IN TENSION

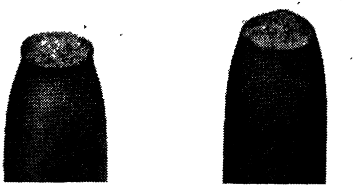

(*a*)

Fig. 13(a). Cup and cone fracture. Indicates good ductility when reduced diameter is small, and low, but helpful, ductility when reduced diameter is large.

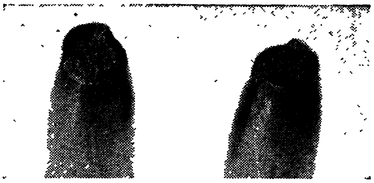

(*b*)

Fig. 13(b). Half cup and cone. A special case of Fig. 13(a). Other forms are one quarter, three quarter, and irregular cup and cone. Terms have no significance except the last which is usually found for low ductility.

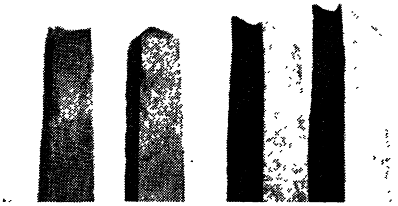

(*c*)

Fig. 13(c). Shear fracture (*right*). May be caused by shape of cross section, but in round specimens indicates that shearing strength is less than one half the tensile strength. [See Equations (2) and (3).] Often found for heat-treated alloy steels.

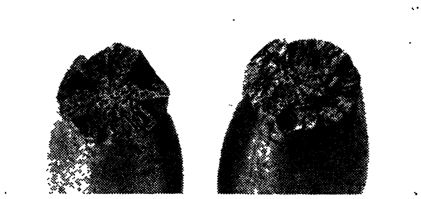

(*d*)

Fig. 13(d). Star fracture indicating internal stresses remaining from heat-treating or severe cold-working operations. Note sharp points and cracks across face of fracture.

DUCTILE MATERIALS IN COMPRESSION

As indicated in the text, ductile materials do not fracture in compression but merely distort plastically or buckle elastically.

BRITTLE MATERIALS IN TENSION

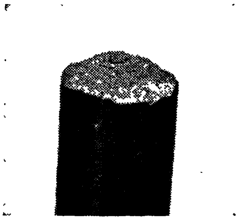

(*e*)

Fig. 13(e). Square break. A true complete tension failure.

BRITTLE MATERIALS IN COMPRESSION

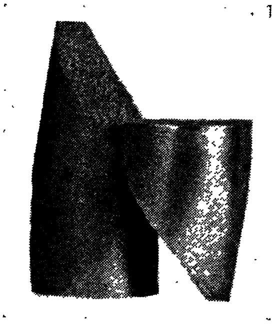

(*f*)

Fig. 13(f). Shear fracture. Same condition as Fig. 13(c) but with the opposite kind of load.

Fig. 13(a) to (f). Types of test fractures for ductile and brittle materials.

of two distinct portions, one light and the other dark. The dark portion is the last to fail, whereas the light section, obviously different in surface appearance, shows evidence of hammering together as the crack spreads. The term fatigue was originally used because it was thought the grains of the material had worn out. Failure due to repeated loading is an important consideration in most mechanical design as, for example, in locomotive side rods, airplane propellers, motor shafts, and high-speed stamping presses.

Wear is seldom investigated in the laboratory, unfortunately, due to the many complications and variables involved in wear testing. Considerably more information needs to be obtained to aid the designer of bearings, rollers, internal combustion engines, and other products which are liable to failure by wear. The more modern concept of this problem is that the surface disintegration, which is external evidence of wear, is due to many repeated loading failures of a relatively few surface crystals.

Most metals and some non-metals tend to go into solution with water in which oxygen is present, or in the presence of moist air. The loss of material in this manner is termed *corrosion*. Failures of this type may be classified as follows:

1. Atmospheric exposure
2. Water exposure (submerged or sprayed, alternately or continuously as the case may be)
3. Soil exposure
4. Chemical exposure (the handling of acids, acidic water, etc.)
5. Electrolytic (stray electric currents which increase the speed of surface disintegration).

Much research has been done to determine the abilities of various materials to resist corrosion, and standard methods of testing are available.

Types of Test Fractures.—A careful examination of a fractured test specimen will give considerable insight into some of the material's physical properties. The student should learn to recognize the types of fractures in conjunction with previous discussion, particularly that relevant to Figure 2 [Equations (2) and (3)]. Various types of fractures are shown and described in detail in Figure 13.

PART TWO

CONDUCTING LABORATORY EXPERIMENTS AND INSTRUCTIONS FOR WRITING REPORTS

In the Materials Testing Laboratory an effort is made to give the student a familiarity with engineering materials and their important physical properties, the manner in which these properties may be obtained, and methods by which the information gained thereby may be presented in graphical and written form. The ability to obtain, compile, and present such information is an invaluable aid to the engineer, not only in experimental work, but also in design.

Purpose of a Report.—While carrying out the specific instructions for conducting the experiments indicated in the text and by the instructor, the student is gaining an understanding of various properties of a material as well as test methods. In some experiments, the former is the more important, while in others the latter will be the primary object of the experiment. In either case, however, the student should acquire the ability to render a brief yet complete and clear report. The student should observe the general form for data sheets and cross-section paper for curve sheets given with each experiment and should be able to prepare such data sheets or curve sheets as may be required by the instructor for additional assigned experiments.

The last portion of the experiment supplies questions to guide the student in written discussion. Questions should be answered in discussion form and such discussion should lead to definite conclusions. The manner of conducting the test should be described and, where possible, results should be compared with standard or average values. The student should look upon the conclusions as though a report were being made of a new material or test method with which anyone else would be unfamiliar.

When submitting reports (unless otherwise indicated by the instructor) additional theory or instruction sheets should be placed first and followed in order by written discussion, curves or diagrams, data sheets, and sample calculation sheets.

Tabulation of Data and Results.—Exercise care to see that all required data are obtained. If anything which may affect the results develops during the test indicate this by marginal or footnotes. While the test is in progress watch for information which will aid in completing the discussion. Data sheets must be neat. When sketches of testing equipment are completed or made by the student, they should be carefully lettered. Never record data elsewhere for subsequent recopying on the data sheet.

Sample Computations.—With most experiments a sample computation outline is provided. On the computation sheet the student should clearly record and illustrate the following:

1. The computations employed in reducing the data to a usable form. Units should be given for each result as, for example, psi., per cent, in. per in., etc.

2. Any computations made to present the test results in the discussion and thereby to state a definite conclusion. Tabular forms should be employed wherever possible for numerical results.

Diagrams and Curves.—The diagrams, presenting visually the statements made in the discussion and conclusions, are the virtual meat of the report. Often a properly drawn diagram will clearly indicate conclusions which perhaps cannot be put into written statements or which would require such a lengthy discussion that they are likely to receive little attention. Most reports are duplicated for submission to many groups who desire the information it contains. The diagrams in such reports are, with few exceptions, reproduced in black and white or as blueprints. This means that color cannot be used to indicate individual curves which may be incorporated or compared on one sheet. It is necessary, therefore, to distinguish between curves by the use of various plotting symbols, type of curve line, or by actual notation on the curve itself. Suggestions for each of these methods are made in Figure 14.

If time permits, the data points should be plotted and the curves should be constructed with black drawing ink. The data points should be plotted with pencil and the curve itself then drawn in with pencil as a guide for subsequent inking. If any plotted points deviate considerably from the trend of the curve the possibility of error in reducing the data or plotting the points should be investigated. When satisfied that all points are correct they should be inked as indicated below. If a straight edge or irregular curve is used to guide the ruling pen when inking over the penciled curve it is advisable to use two of either implement. The first straight edge or irregular curve is then placed on the paper adjacent to the plotted and previously inked data points, but not touching them. The second straight edge (or irregular curve) is then placed over the first and in line with the penciled curve. As the ruling pen follows the penciled line the ink will run into the inked points but cannot be sucked under the guiding edge to spoil the curve.

Plotted points should be of such a size that they can be inscribed within a square approximately 0.1 in. on a side.* The curve should be drawn between these points and not through them. Each plotted point represents experimental data and the curve is the investigator's interpretation of the entire data. A completed experimental curve is included with Experiment 12. Place name and date of the experiment on the curve sheet.

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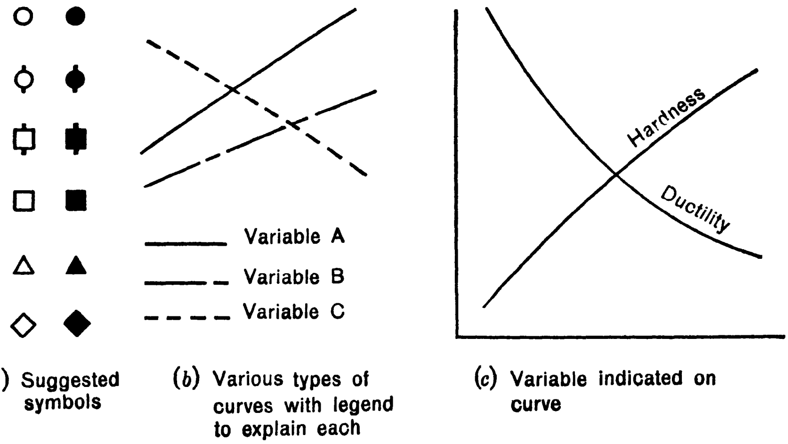
* Cross-section paper ruled 20 lines per inch is commonly used for plotting or graph paper but often represents a needless refinement or causes a confusing scale of coordinates. Cross-section paper ruled 10 lines per inch may also be used.

Use smooth curves between plotted points for presentation of all data except calibration. When constants or errors, observed for various loads or readings, are obtained from the calibration of some device the points should be connected with straight lines.



(*a*) Suggested symbols (*b*) Various types of curves with legend to explain each (*c*) Variable indicated on curve

FIG. 14. Manner in which data may be presented in diagrams and curves.

In many experiments the units of the coordinates are given on the sample curve sheet. For those tests where size of specimen, span length, type of material, or other variables influence the selection of units for the coordinates, units should be selected so that the trend of the data is clearly indicated but so that experimental errors are not given undue prominence.

Class Organization in the Laboratory.—Experiments will be conducted as demonstration tests or as squad tests. Three or four students will constitute a squad which will be divided as follows:

1. Operator, who will manipulate all testing equipment except that used by the observer, and who will indicate any load requested by the observer.
2. Observer, who will make all the readings and observations required except the determination of the load indicated by the testing machine.
3. Recorder, who will place all data in its proper place on the data sheet, and who will ascertain the fact that the observer secures the data required to complete the experiment.

In some experiments these duties will overlap or additional duties will arise. These should be shared by the squad members in the most effective manner. The duties of each man will be approximately evenly divided between that of operator, observer, and recorder throughout the course.

The squad should complete its own data and computations as a unit. If four men are on a squad one may act as a computer to expedite the reduction of the data.

Significant Figures.—Most computations employed in analyzing the data may be made with sufficient accuracy with the slide rule. Calibration data is an exception to this statement. Use the same number of significant figures in the completed results as was obtained in the original data. Should two items of measuring apparatus be used the one giving the result with the least significant figures will govern the final result.

Reference to Standards.—Whenever possible reference will be made to standard test methods or specifications. This insures the student of a familiarity with reference material which he will continuously use in his design work. In this course the student is expected to have access to a copy of the latest revision of "Selected A.S.T.M. Standards for Students in Engineering" published by the American Society for Testing Materials. This organization, composed of over 5000 engineers and companies who are interested in the manufacture, use, testing, or study of engineering materials, is most actively engaged in the formulation and publication of standards governing test results. The A.S.T.M. cooperates closely with other technical societies and groups interested in standardization. It also encourages research in engineering materials and dissemination of the knowledge thus gained by sponsoring its own research projects and technical meetings. The technical papers presented at these meetings are published annually in the "Proceedings" of the Society.

A.S.T.M. Standards are designated by codes which indicate the class of interest in which they are grouped. Such a designation would be E4-36. The various designations are made according to the following code:

1. Letter prefix indicates the type of material or nature of the standard:

A = Ferrous Metals
B = Non-Ferrous Metals
C = Cementitious, Ceramic, Concrete and Masonry Materials
D = Miscellaneous Materials
E = General Testing Methods, Definitions, Metallography, Spectrochemical Analysis

2. Number following the letter is a serial designation of the standard in its particular group.

3. The final number indicates the year of issue or adoption of the standard. If a standard has been revised this final number indicates the year of revision. A standard that has been adopted tentatively has the letter "T" appended.

PART THREE

EXPERIMENT 1

TESTING MACHINES THEIR USE AND CALIBRATION

The first systematic investigator of the strength of materials was Galileo who, in 1635, wrote about cohesion and the resistance of materials to fracture. His tests on tenacity led him to state that if a copper rod "4800 arms" in length could be suspended by one end it would break near the suspended end due to its own weight. About the beginning of the eighteenth century fundamental investigations were being made of the physical properties of the materials of the civil and mechanical engineer. These early tests covered the usual conditions of tension, compression, and bending. One of the first applications of these test results to actual practice was in the construction of a bridge across the Seine at Neuilly-Sur-Seine in 1658. Jean Perronet, the engineer in charge of this work, constructed a 36,000-lb. capacity testing machine to check the strength of the material used in the construction. The success of this machine led to the use of similar machines for testing the materials used in buildings, bridges, and harbor works. With the invention of the steam engine the mechanical engineer found it necessary to know the properties of materials in order to permit concentrations of power without failure. As early as 1829 riveted joints of various types, as well as large sized iron and steel sections, were being tested.

Today the materials testing laboratory continues to aid in the development of new engineering materials. Fundamental tests to determine the tensile and compressive strength of new metallic alloys, plastics, etc., must always be made. These routine tests, as performed by the hundreds every day in all steel mills and metal working plants, are merely control tests to guide the manufacturer so that the final product will meet the required specifications. Interesting and unusual tests of this type are made on adhesive tape, paper, cord, yarn, cloth tape, fiber-glass tape, aluminum foil, and fine wire. Machines so sensitive that they will measure the breaking strength of a human hair are used for such work.

Large capacity testing machines have proven their worth since they permit the testing of full sized parts rather than doubtful models. Most research organizations use testing machines capable of exerting very large loads. Tests of full sized locked railroad car couplers may be made to determine their breaking strength or weak point. Some testing machines may be used to study locomotive side rod and crosshead assemblies, large riveted joints, concrete slabs, and many other parts. Machines of this type are shown in Figure 15 and the frontispiece. Using the principle of the strain gage explained in Experiment 14 it is easily possible to determine which parts of the test specimen are overloaded and underloaded. The consequent economy of design resulting from the reduction of section thickness, unnecessary stiffening ribs, or improperly placed rivet and pin holes more than repays the cost of the test. These large testing machines may also be used as forging presses in the study of metal working. The knowledge gained from the study of metal while in the plastic range has led to improved design of metal forming presses, stamping machines, and extrusion presses.

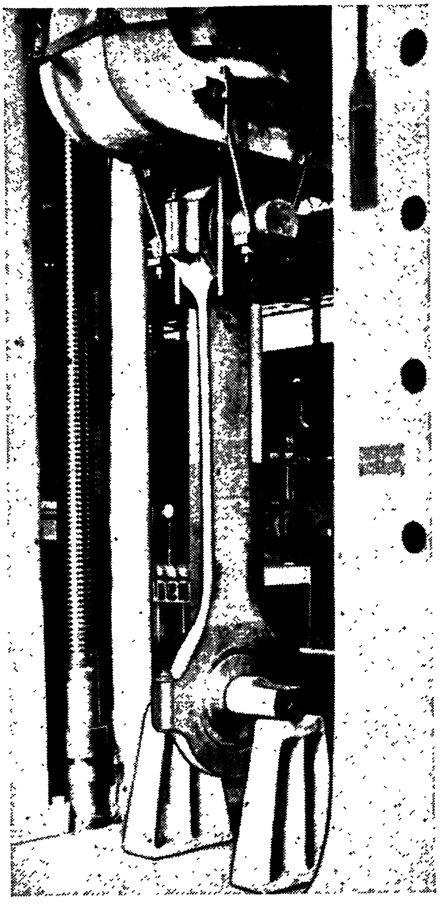


Fig. 15. Locomotive connecting rod undergoing test in a 1,000,000-lb. universal testing machine. (Courtesy C. and O. Railway and Baldwin-Southwark)

This first experiment is intended to acquaint the student with the component parts, the method of operation of several types of testing machines, the manner in which they may be calibrated, and some of their uses. A knowledge of how loads may be applied and measured is a valuable outcome of this experiment which is often helpful in testing full sized specimens.

Construction of Testing Machines

Three types of testing machines are employed for static testing, as follows:

1. *Dead Load Type.* For testing small wires, cloth, glued joints, or any other condition where small loads are required and must be weighed

accurately, it is advantageous to apply dead load to the specimen. The load may be obtained with small BB shot, water, or calibrated weights. Many large structures are tested by applying dead load in the form of pig iron, bricks, sand, sandbags, or any like material. Such tests usually are not carried to destruction because of the large number of weights required.

When leverage is employed with dead load the mechanical advantage is introduced and the quantity of weights required is reduced. The load must still be manually applied or removed, however.

2. *Mechanical-Lever Type.* When the load is applied mechanically rather than manually and weighed through a system of levers, as will be explained later, the machine is said to be of the mechanical-lever type.

3. *Hydraulic Type.* Some testing machines employ a hydraulic loading system with which to apply load to the specimen. This load may also be weighed in the same manner (by the use of hydraulic gages), or through a lever system similar to that in some of the mechanical-lever types.

A testing machine consists of two separate and independent parts, the weighing system and the loading system. The function of each part is as follows:

1. *Weighing System.* In order to determine the strength or load-carrying capacity of a material or part, it is necessary to weigh the test load applied to a test specimen. The weighing system of some testing machines is nothing but a large capacity scale.

2. *Loading System.* To avoid the inconvenience of laboriously placing or removing dead load on the test specimen as it reacts on the weighing system, a separate, independent loading system is provided. This loading system usually offers a variety of speeds and manner of application of load. The only connection between the two systems is through the test specimen. As load is applied to the specimen by the loading system, the specimen, when below its ultimate capacity for load, reacts on the weighing system so the load may be measured.

A sketch of the weighing system of a mechanical-lever machine is shown in Figure 16. The compound levers, also called double levers, take the reactions from the four corners of the weighing table and transmit them to a link as shown. Notice that knife edges are employed wherever motion changes direction. The link reacts on a middle or intermediate lever which in turn reacts on the weighing or scale beam. A poise may be moved along this beam to some position where it will exactly balance the load on the weighing table. By arranging the levers of the mechanical-lever type machine in this manner it is possible to obtain a large lever ratio in a small space. The lever ratio varies for different machines but, in general, is about 2000 to 1. That is, 1 lb. on the weighing beam will balance 2000 lb. on the weighing table. This value, when exactly given for the machine and after the levers have been measured and the poise weighed, is called the *pound equivalent.* In order to place the entire weighing system in approximate balance, a counterweight is added as shown in Figure 16. To obtain exact balance at the zero load position, or to balance out the weight of specimens or any auxiliary equipment which ordinarily rests on the weighing table, it is necessary to use a counterpoise. This device then permits exact zero balance of the poise and beam.

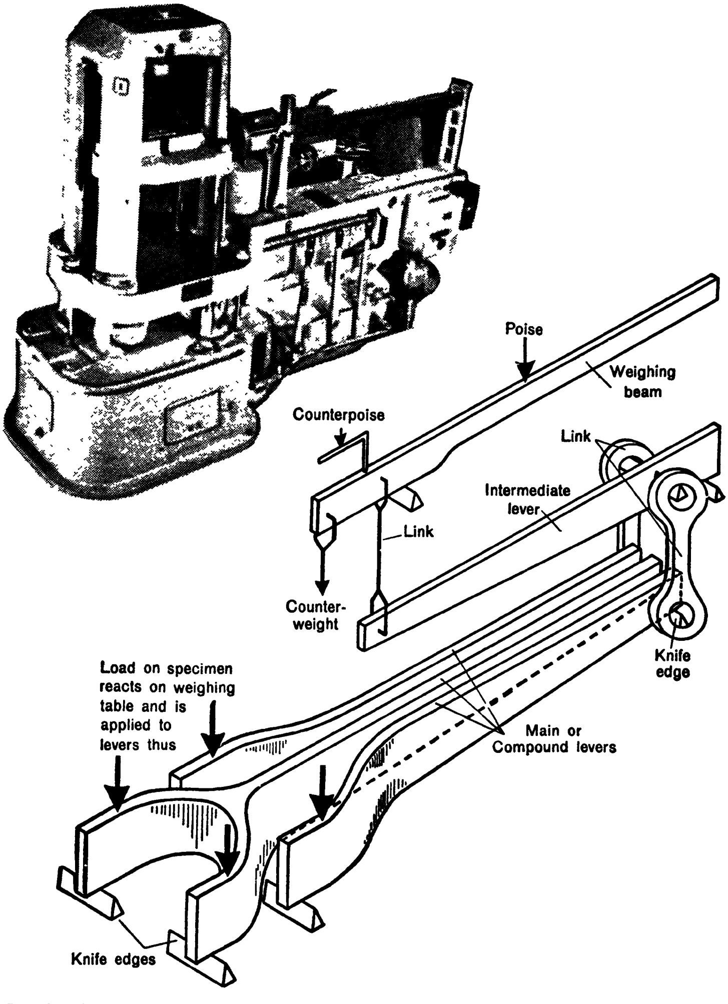


FIG. 16. Weighing system of a universal testing machine of the mechanical-lever type.

In the hydraulic type of testing machine the load may be measured in one of the following two ways:

1. A hydraulic capsule may be placed between the loading system and the specimen or between the specimen and some part of the testing machine against which it reacts. In either case the hydraulic capsule is the

weighing system. As load is applied to the capsule, oil is forced out and the pressure required is indicated by a pressure gage. The advantage of this method is that only the true load on the specimen is weighed.

2. In some hydraulic testing machines the load is indicated by merely measuring the oil pressure in the hydraulic loading system. Some load may be lost in friction between the piston and cylinder, so that the pressure or load in the hydraulic system may not be a true indication of the force applied by the loading end of the piston. This method of weighing load is liable to more error than the method previously explained and is therefore not as desirable.

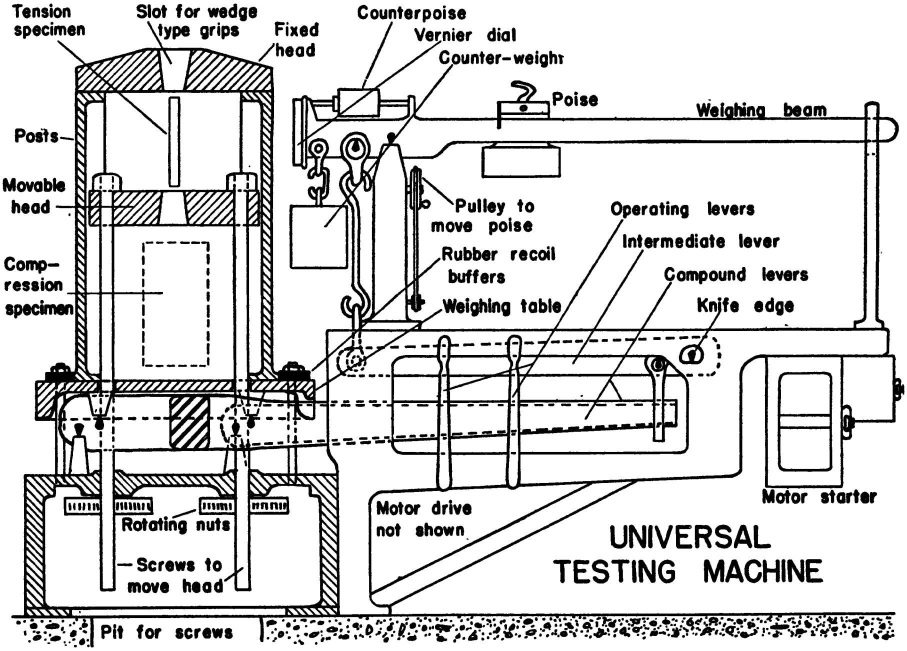
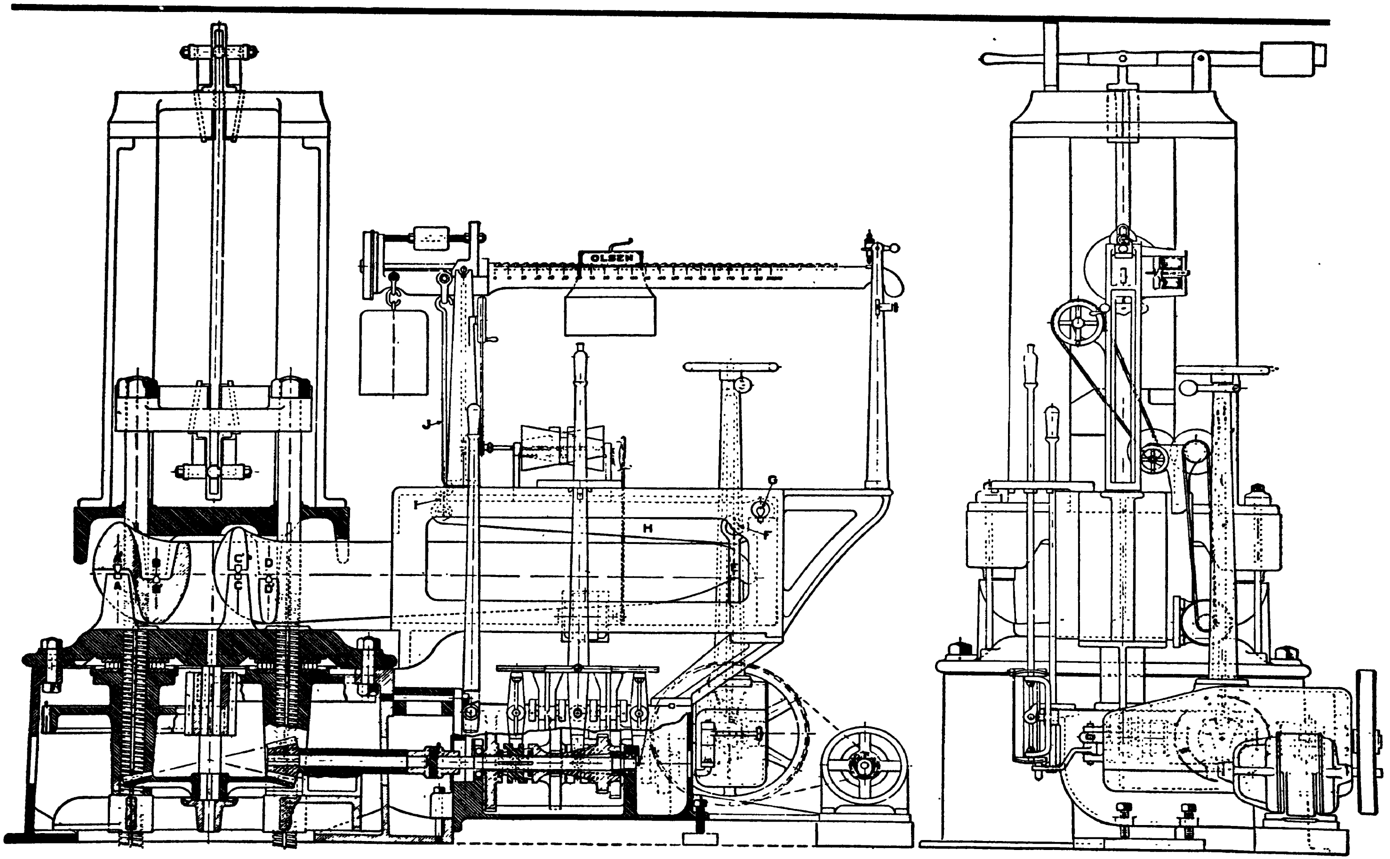


Fig. 17. Component parts of a mechanical-lever type universal testing machine.

Since the load applied with hydraulic testing machines is shown by a self-indicating dial it is easily read and requires but little attention by the operator. For this reason these machines have been used in increasing numbers for routine and production testing. Mechanical-lever type machines are also available with a pendulum replacing the weighing beam so that the load may be automatically weighed and indicated on an easily read dial. This is still considered a mechanical-lever system, however. The hydraulic loading system and the pendulum weighing system with self-indicating dial may also be combined, as shown in Figure 19(a).

The component parts as well as detailed drawings of the mechanical-lever type of testing machine are shown in Figures 17 and 18. A



OLSEN UNIVERSAL TESTING MACHINE

FIG. 18. Four-screw, rotating gear nut type, with automatic beam and automotive quick-change, eight-speed reverse gear box drive. (Courtesy Tinius Olsen Testing Machine Company)

mechanical-lever type of machine, with which a self-indicating dial is coupled, is shown in Figure 19(b).

The crosshead or moving head of a mechanical type machine may be actuated in two ways. As shown in Figures 17 and 18 the rotating nuts, which are also gears, are turned on the loading screws. Inasmuch as these rotating nuts are fixed in place by the base casting the screws must move up or down and the head with them. If the loading screw is threaded over its entire length and held in place by the base casting, the screw may be rotated to cause the head to move up or down. This system is called the rotating screw type. Load is transmitted by the specimen to the weighing system in either case.

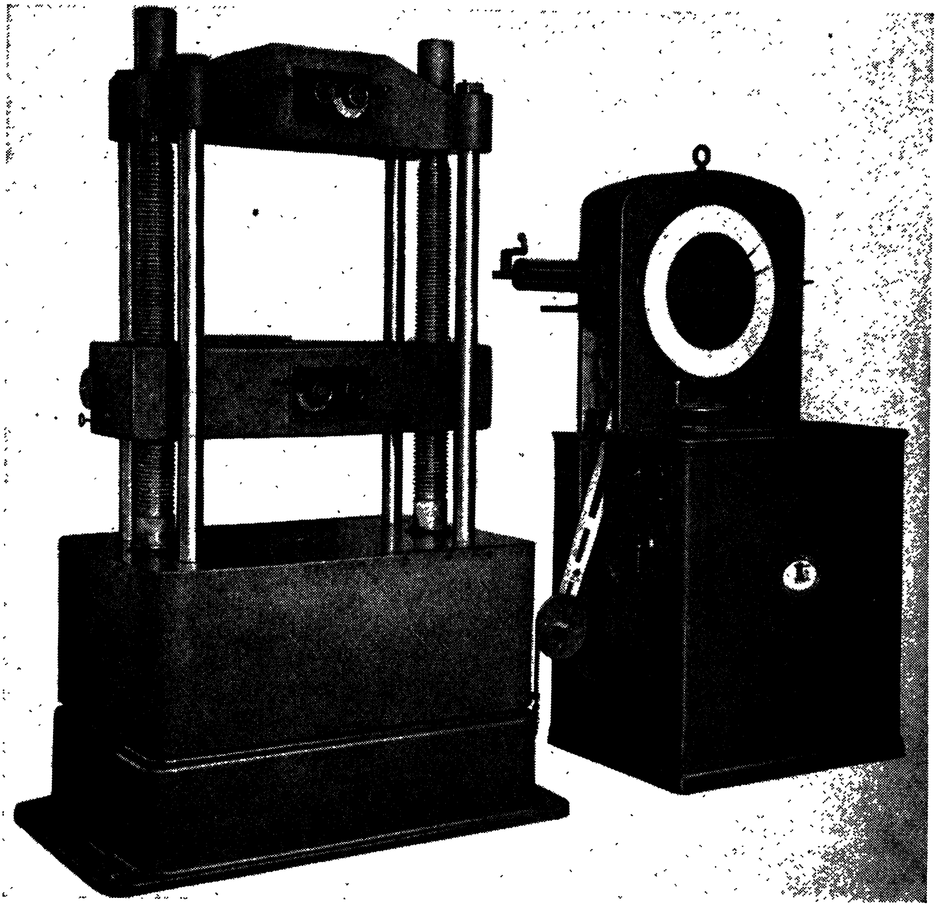


FIG. 19(a). Riehle Universal Hydraulic Precision Testing Machine employing pendulum load weighing system with self-indicating dial. (Courtesy American Machine and Metals, Inc., Riehle Testing Machine Division)

A hydraulic type of testing machine using hydraulic weighing is shown in Figure 20. The details of the component parts of this type of machine are given in Figure 21. Notice that the surface on which a compression specimen rests in the hydraulic machine is called a *platen,* in contrast to the weighing table of the mechanical-lever type of machine. The platen of the hydraulic machine moves upward and with it the fixed crosshead as shown in Figure 21.

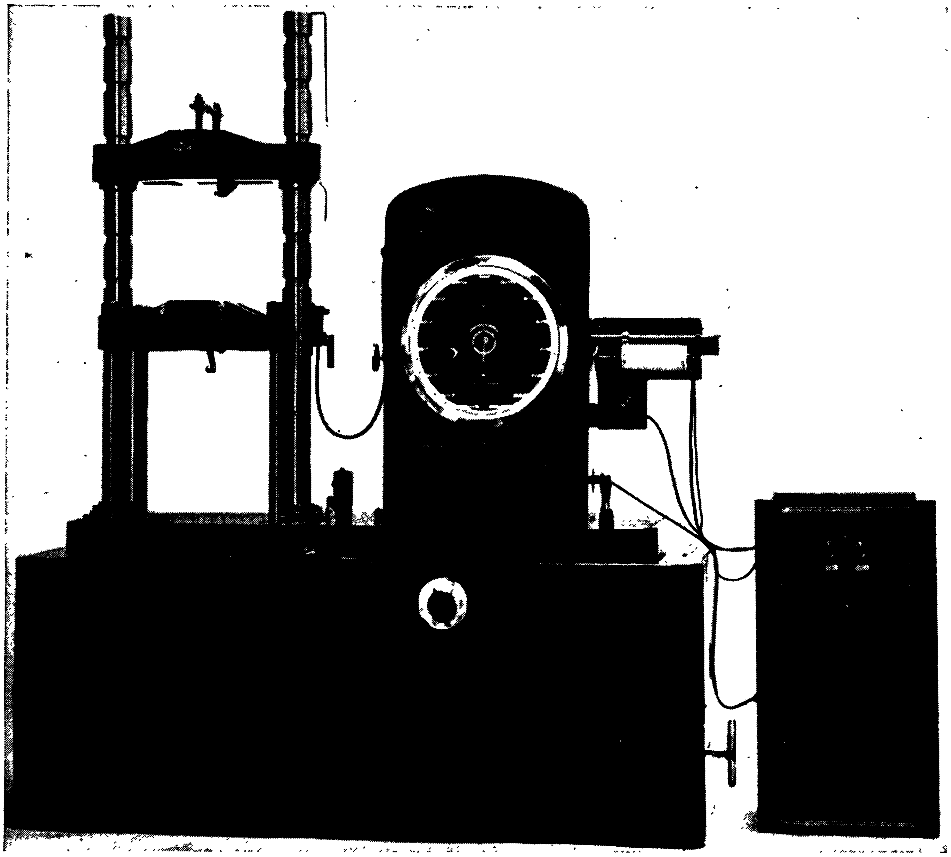


Fig. 19(b). Mechanical-lever type testing machine with self-indicating dial. Automatic stress-strain recorder also shown. (Courtesy Tinius Olsen Testing Machine Company)

In most testing machines the specimen is maintained in a vertical position during the test. The vertical type of testing machine requires considerable head room and may not be feasible for testing long columns, wire rope, chain, and other long specimens. The horizontal type of machine provides for the testing of these long members with no increased head room, although the floor space must necessarily be increased. A horizontal testing machine differs from the vertical type only in that the loading system is placed in a horizontal position. Testing machines capable of applying tensile or compressive loads are called "Universal" machines. Most machines are of this type.

Some testing machines have supports for beam tests built into the weighing table or readily attachable to it. Such a machine is shown in Figure 22. When large parts cannot be placed in a testing machine because of limited space or capacity it is often convenient to use a floor test slab or *force slab* on which to perform the test. The force slab consists of a heavily reinforced concrete block 3 to 6 ft. thick and from 10 to 20 ft. long or wide. In this block are cast threaded receptacles for long, high-strength, steel rods. The rods are firmly screwed into the receptacles in whatever position they are needed. Each such receptacle or insert has a capacity of from 10 to 40 or more tons, depending upon the length and size. A heavy steel member placed across the tops of the rods may then be used as a rigid support against which a hydraulic jack, mechanical screw jack, or a lever with dead weight may react to apply load to some

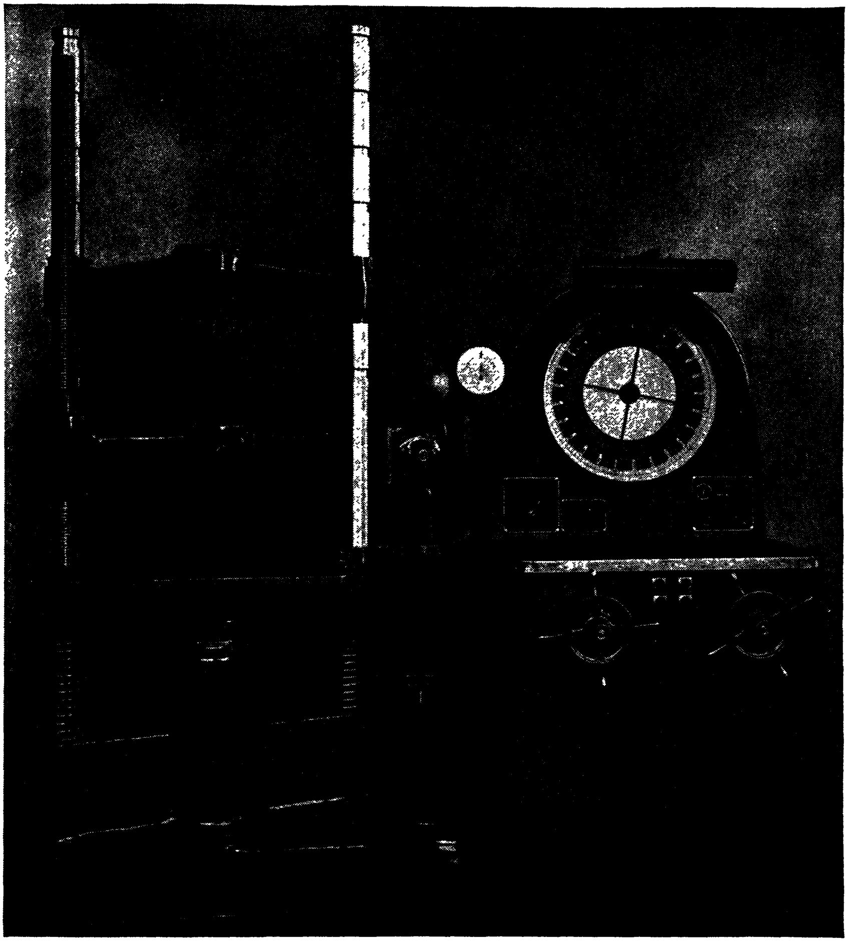
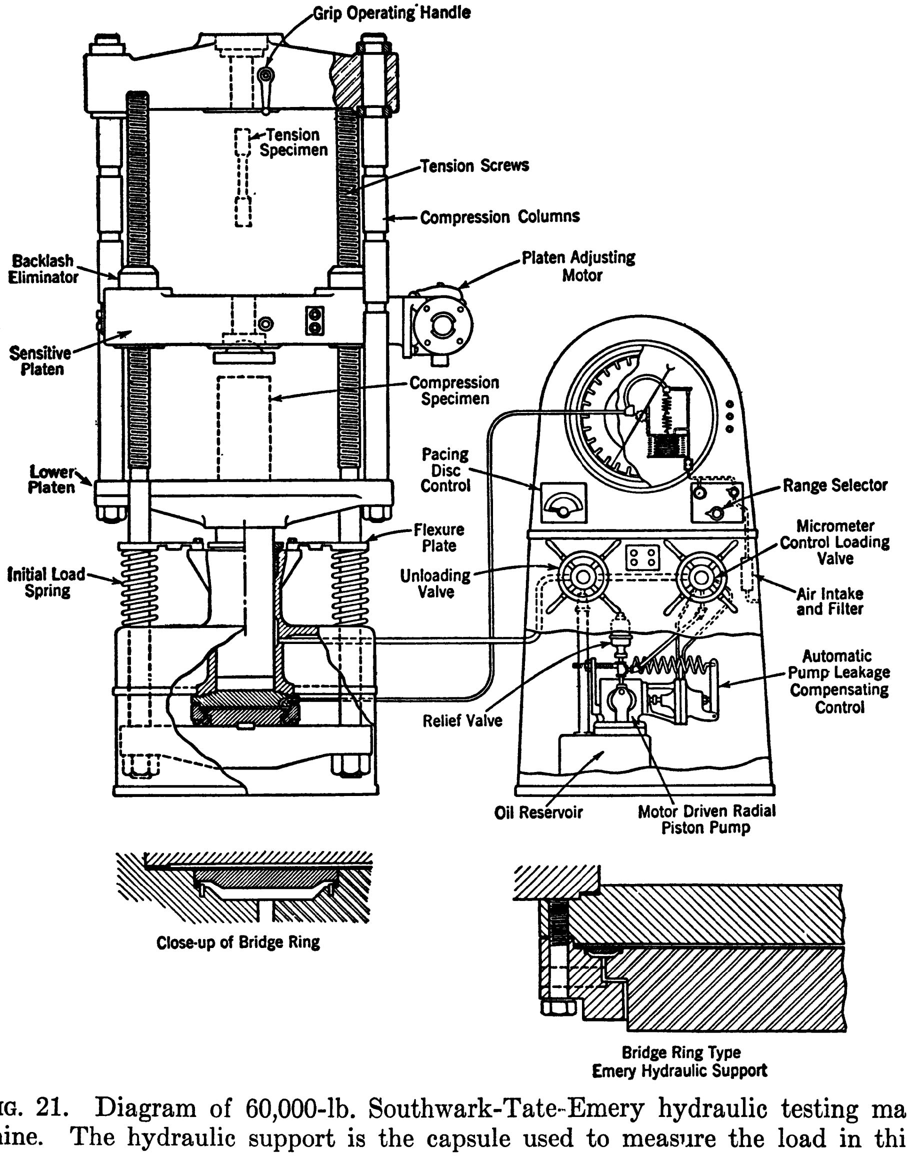


FIG. 20. Southwark-Tate-Emery 60,000-lb. capacity hydraulic testing machine. (Courtesy Baldwin-Southwark)

part being tested. This method of loading, when coupled with an elastic calibrating device is adaptable to most large scale testing work. In Figure 23 is shown such a floor test slab with a specimen in place.



Close-up of Bridge Ring

Bridge Ring Type Emery Hydraulic Support

FIG. 21. Diagram of 60,000-lb. Southwark-Tate-Emery hydraulic testing machine. The hydraulic support is the capsule used to measure the load in this machine. (Courtesy Baldwin-Southwark)

A unique application of the hydraulic capsule used in testing machines has been made in many steel mills. The capsule is placed above the top roll of a rolling mill and the pressures required to roll steel shapes are easily obtained by observation of a hydraulic gage. Prior to the adoption of this method roll pressures were virtually unknown because they were

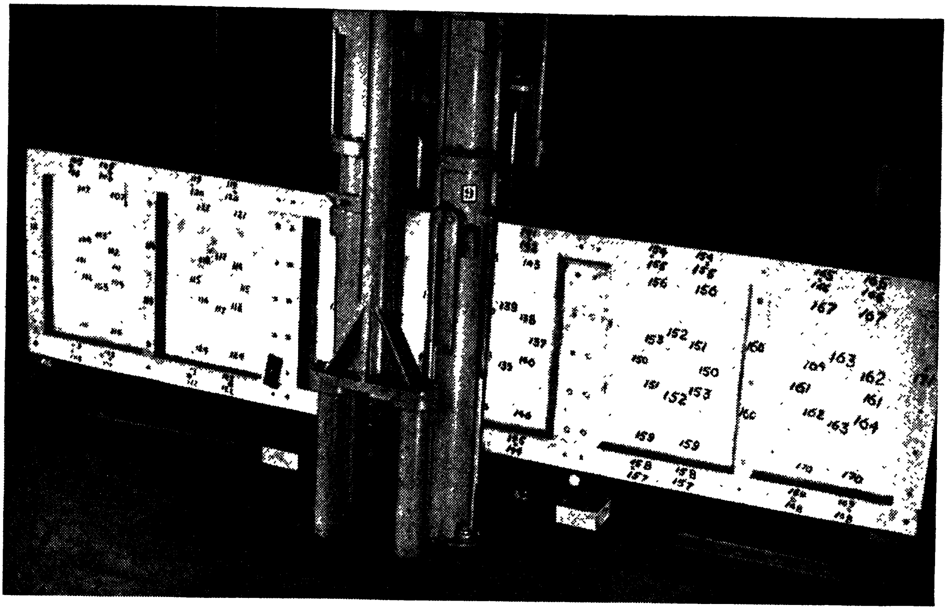


FIG. 22. Eighteen-foot span plate girder made of plywood and dimension lumber being tested in 400,000-lb. capacity testing machine. Girder rests on supporting beams which are part of the weighing table. This supporting beam may be seen in slot in floor. Numbers on girder show location of strain-gage lines.

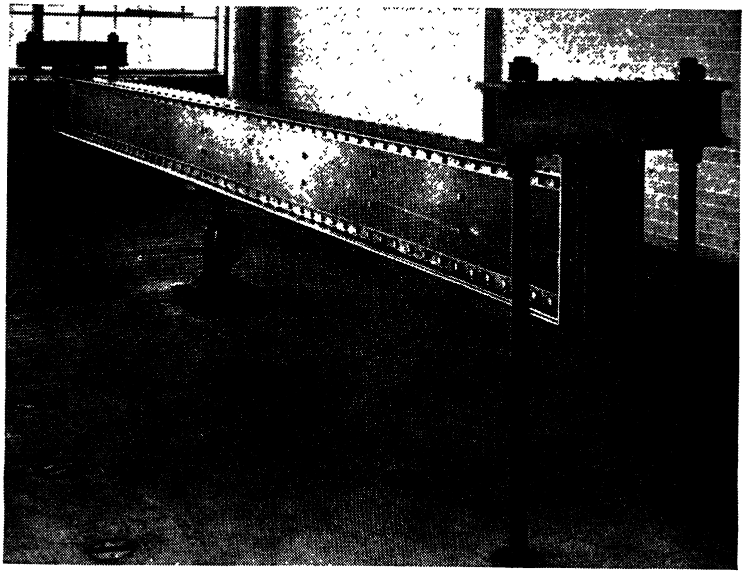


FIG. 23. Universal (tension or compression) floor test slab 12 ft. wide and 30 ft. long. Each of the 48 inserts is capable of withstanding a pull of 25 tons. An aluminum alloy girder is shown in position for test with a 30-ton hydraulic jack to apply load. (Courtesy Aluminum Company of America)

difficult to measure. A knowledge of these pressures has resulted in revised roll designs and has prevented many roll and bearing failures. Inasmuch as the pressures may be automatically recorded on a continuous chart they may be used to indicate when billets are not properly preheated before rolling. When the pressure is too high the billet has not been in the soaking pit long enough and may need to be returned. Proper control of preheating temperatures and thus of rolling pressures has permitted the rolling of continuous sheet and plate of carefully controlled thickness, has improved the surface quality of finished steel, and has reduced power costs.

The weighing system of the testing machine, regardless of type, is subject to deterioration due to wear and other causes. Such deterioration reduces the accuracy and sensitivity of the weighing system and constant care must be exercised therefore so that such loss is not excessive. The following factors govern the accuracy of the mechanical-lever type testing machine:

1. *Condition of Knife Edges.* As shown in Figure 16 knife edges are used in the weighing system wherever motion changes direction. These knife edges are normally sharp so that lever distances are clearly defined. When the knife edges are dull, however, the lever distance may not only be incorrect at the beginning of the loading action but may actually change during the slight rotation which accompanies loading.

2. *Original Calibration.* Unless the scale beam and vernier dial of a testing machine are correctly calibrated when the machine is manufactured it will obviously be in error.

The sensitivity of the testing machine is its ability to respond to slight changes in load. Many types of measuring devices are accurate but not sensitive. Although not as essential as accuracy, the sensitivity of a machine is of major importance. This characteristic depends solely upon the condition of the knife edges. If they are dull the machine is sluggish and loads must be applied at very slow speeds to be properly weighed. Failure to adjust the recoil buffers properly is probably the greatest single factor contributing to lack of sensitivity in a lever type of weighing system. When the test specimen ruptures, the sudden release of load causes the weighing table to lift suddenly. This recoil is absorbed by properly adjusted recoil buffers which prevent the table from rising off the knife edges and their seats and thus falling back and dulling the sharp edges.

The accuracy of a hydraulic testing machine will depend on the type of weighing system used. The hydraulic capsule, being a closed oil pressure system, is subject to considerable inaccuracy if any air should enter the system. Actually the error observed when this condition exists is sometimes found to be as much as 25 per cent. This is an extreme case, however, and indicates a lack of periodic checking. In addition to the possibility of inaccuracy in the capsule, the load-indicating gages are also subject to possible mechanical error. This latter condition may usually be corrected by minor adjustments provided with the machine. When the hydraulic capsüle is used with a pendulum weighing device the possibility of inaccuracy in the load indicating device is reduced. In the hydraulic type machine in which the load is obtained from the pressure in the hydraulic system, error is introduced due to friction between the piston and cylinder, as previously mentioned. When the piston is near the limit of its travel in the cylinder, this friction, and consequently the error, is usually less. The load-indicating device is subject to the same error previously mentioned for the other type of hydraulic machines.

The most important factor influencing sensitivity in the hydraulic testing machine is entrapped air in the hydraulic system. Such a condition makes the indication of load very erratic and apparently sluggish. If the mechanical part of the load-indicating apparatus of the hydraulic testing machine is not sensitive by virtue of its design it can rarely be improved.

Speed of testing is an important factor in test results. Generally, satisfactory results will be obtained with the weighing beam type of machine if the load is not applied at a rate faster than that which can easily be balanced. Since the self-indicating dials are not restricted by manual operation the tendency is to use these machines at too high a speed. Testing speeds are most intelligently given as one of the following:

1. Rate of movement of loading head in inches per minute for a given diameter and length of specimen.
2. Rate of strain of specimen in inches per inch per minute over specimen length.
3. Rate of load increase in pounds per minute for a given diameter of specimen.

To provide for (3) many testing machine are now equipped with pacing disks calibrated to provide a wide range of loading speeds. High speed should be used only for adjusting the head to position for the test.

Both mechanical and hydraulic testing machines may be fitted with devices to permit several loading ranges.

CALIBRATION OF TESTING MACHINES

The A.S.T.M. specifies that "the error for loads within the loading range of a testing machine shall not exceed 1 per cent" (see A.S.T.M. Designation E4-36). It is desirable, however, to have the error within 0.5 per cent. No specification is given for sensitivity, although it is usually within 0.05 per cent of the applied load. A testing machine may be calibrated in one of the following ways:

1. By the use of dead weights. Impractical except for small capacity machines.

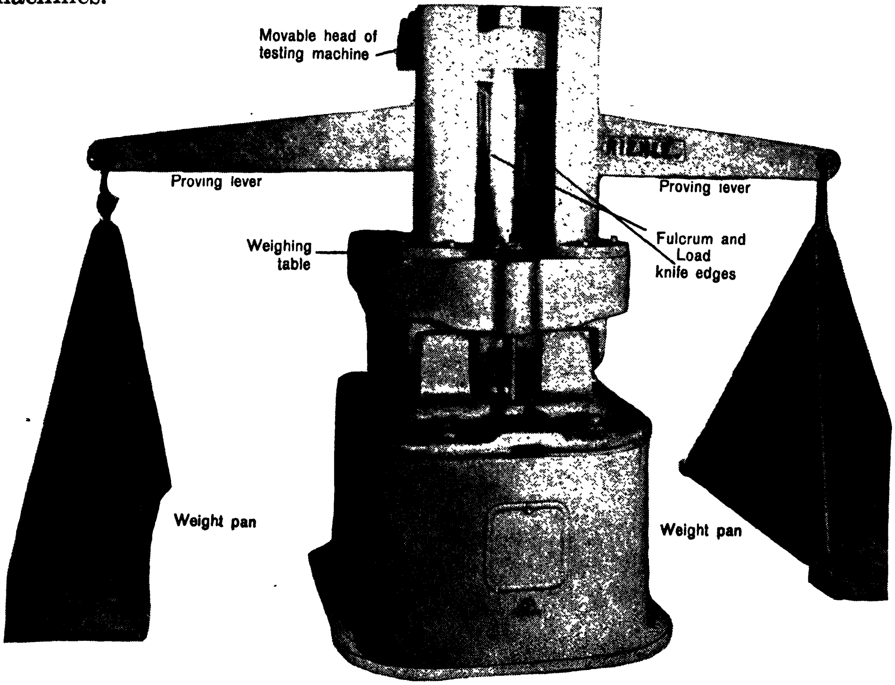


FIG. 24. Proving levers in place for calibrating a testing machine.

2. By the use of dead weights and levers with which to obtain a mechanical advantage. These levers are called *proving levers.*

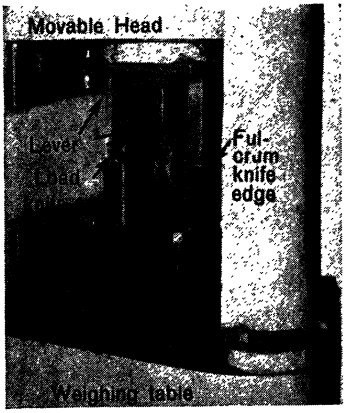


FIG. 25. Detail of fulcrum and loading knife edges of proving levers.

3. By the comparison or companion bar method. Specimens tested in a machine are compared for tensile strength with companion specimens tested in a machine of known accuracy.

4. By the aid of an elastic proving device.

5. By the aid of a hydraulic device employing the hydraulic lever. Only methods 2 and 4 will be discussed here.

Proving levers are shown in place in a testing machine in Figures 24 and 25. Weights are placed on the weight pans shown in Figure 24. This load is hung on the proving levers and they in turn fulcrum about points on the fixed head and apply load to the weighing table. All loads are applied through knife edges as shown in Figure 25. A level gage is used to ascertain that the levers are horizontal. After each increment of weight is applied it is necessary to lower the movable head of the testing machine to bring the levers to a horizontal position and thus maintain the correct lever ratio. For most proving levers the lever ratio is 10 to 1.

A simple form of elastic proving device may be obtained with a solid or tubular steel specimen and a strain gage of any type discussed in Experiment 14. The block is carefully measured to determine the cross-sectional area and then placed in the testing machine in tension or compression. As each selected load is applied the strain in the specimen is measured and the stress may be computed from the relationship $E = s/\epsilon$ of Equation (7), since E is known. The average unit stress times the cross-sectional area is then the correct load.

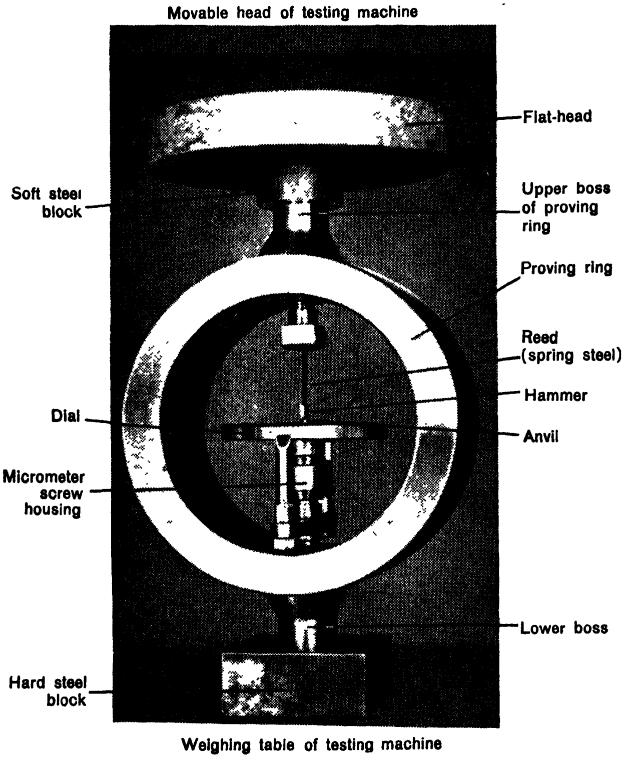


Fig. 26. Morehouse elastic proving ring. Manufactured by Morehouse Machine Co.

The most versatile of the elastic calibrating devices is the proving ring. In Figure 26 are shown the essential parts of a Morehouse proving ring. These rings are machined from solid steel forgings, carefully heat-treated and manufactured, and then calibrated by the National Bureau of Standards. They are available for either tension or compression loading, or for both. When the ring is used it deforms elastically under load and this deformation, when carefully measured, is used to determine the load. Rings used for calibrating must be accurate to within 0.2 per cent of the true load for comparative purposes, but are considered to be perfect.

Elastic proving devices are often termed dynamometers and have many applications other than calibrating testing machines. These applications include the determinations of the total force which a metal working press is capable of exerting, the load applied to a large test specimen with levers and random weights, the drawbar pull which a railroad locomotive exerts, as scales for weighing large loads, and in structural work for checking the reaction (and thus an important assumption made in design) of a continuous bridge span on an intermediate support. An example of this last application is shown in Figure 27.

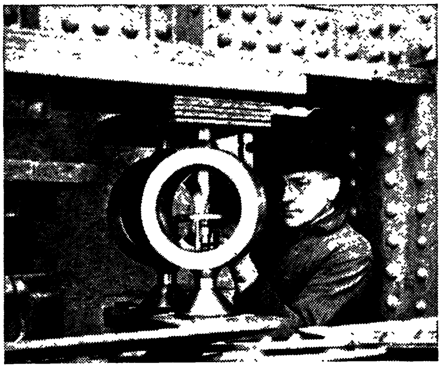


FIG. 27. Morehouse elastic proving rings being used to weigh the reactions of the Bourne Highway Bridge over the Cape Cod Canal. (Courtesy American Bridge Company)

EXPERIMENTAL PROCEDURE

Study of a Testing Machine

APPARATUS—A universal testing machine of any capacity but of the mechanical-lever type.

Examine the testing machine carefully, following the descriptive text and Figures 16 through 18. Accompanying the experiment is a photograph of a universal testing machine of the mechanical-lever type, Figure 28, on which the following items should be indicated.

1. Knife edges and their seats
2. Weighing table
3. Recoil buffers
4. Loading screws
5. Movable head
6. Fixed head
7. Vernier dial
8. Counterpoise
9. Poise
10. Weighing beam
11. Counterweight
12. Control to move poise
13. Intermediate lever
14. Compound or double levers

When these items have been shown on Figure 28 a table similar to the following should be filled out for the machine examined:

Name or number of machine ....
Capacity, pounds ....
Type of weighing apparatus ....
Type of load-indicating apparatus ....
Vertical (a) or horizontal (b) ....
Number of loading screws ....
Rotating nut (a) or rotating screw (b) ....

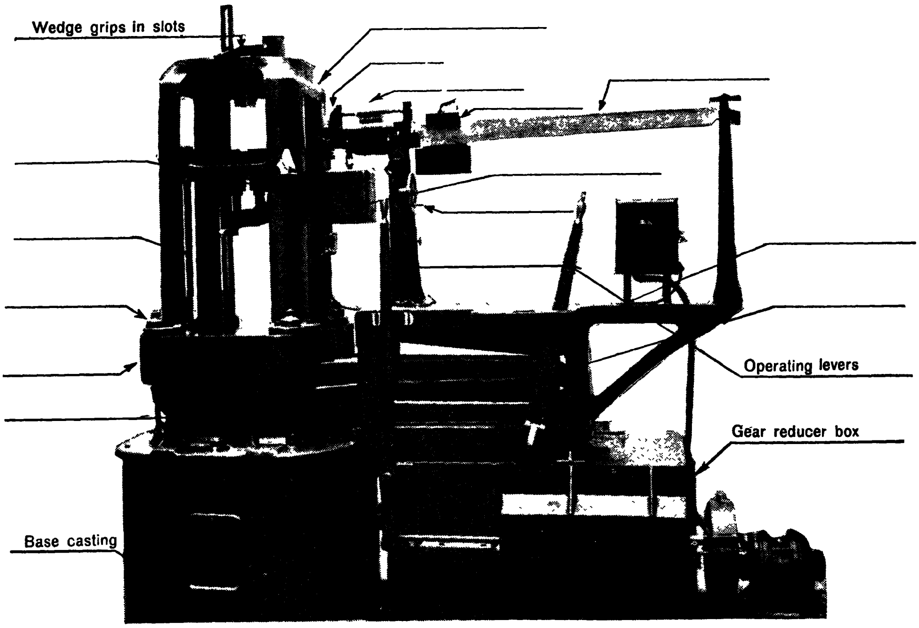


FIG. 28. Sample sheet showing various parts of a mechanical-lever type of universal testing machine. The items indicated in the experiment are to be noted in their proper places on a sketch or photograph similar to this. (Courtesy Tinius Olsen Testing Machine Company)

CAUTION: In this and succeeding experiments operators of the machines will be held responsible for any damage to equipment resulting from carelessness. Carelessness will be minimized if the following routine is observed when using machines:

1. Make sure that the clutch lever is in the neutral position.
2. Make sure that the line switch is in the "off" position and that the control lever on the starting box returns to the "off" position when leaving the machine.
3. When starting, or changing speed by moving the gear shift lever, the clutch lever should be in the neutral position.

4. The motor should be allowed to come to a stop before reversing its direction.

5. Balance the weighing beam or bring the dial pointer to zero before starting the test.

6. The small edge of the grips should be from ¼ to ½ in. inside the crosshead to prevent breakage. It may be necessary for small specimens to insert sufficient liners between the grips and the head to maintain this clearance. The liners should be placed symmetrically with the same number or total thickness on each side of the grips.

7. Grip the specimen over the entire grip length to prevent damage to the specimen or the grips.

8. Grips are made of hardened steel to permit the teeth to bite into the specimen. They may stick in the slots which hold them. In such a case do not strike them with a steel hammer, but use a soft copper or lead hammer.

9. Recoil buffer nuts should be adjusted so they just contact the weighing table at zero load, and should not be tightened.

10. Never leave the controls of a machine when it is running.

11. Never test at high speed.

Special precautions to be observed with hydraulic machines are:

1. Force the piston slightly out of the cylinder before adjusting the movable crosshead. If this crosshead should then accidentally stall against the lower platen, or a specimen, it can be freed by lowering the platen.

2. Never test with the piston almost at the limit of its travel out of the cylinder. This condition causes excessive piston wear. Also sufficient travel may not remain to complete the test.

If unfamiliar with a testing machine consult the instructor.

Calibrating a Testing Machine

APPARATUS—A proving or calibrating device or method and a universal testing machine of any type and a capacity in keeping with the capacity of the proving device.

If a machine is calibrated with proving levers the procedure outlined previously should be followed. The companion bar method and the other methods are explained in A.S.T.M. Designation E4-36, which should be consulted.

Before the proving ring is placed in the testing machine, turn the dial of the proving ring around six times away from contact with the reed hammer. This should be done to insure ample space for maximum load deflection. Should the hammer contact the anvil during loading, the reed might bend and cause appreciable change of the zero reading.

Place a flat, smooth, hard steel plate on the weighing table of the testing machine and stand the proving ring on this plate so that it rests on the lower boss. Place a plate of soft steel on the rounded end of the upper boss and apply a pre-load to the ring equal to the maximum load to be applied. Remove the load but do not disturb the soft steel plate on the upper boss.

The zero reading of the micrometer dial should now be obtained. To read the dial, turn it until the anvil is almost in contact with the hammer. Set the reed in motion with a pencil by moving the hammer about ½ in. to one side and then releasing it. While the reed is vibrating, turn the dial slowly until the anvil contacts the hammer. Contact is indicated by a buzzing musical sound. Read the dial to 0.1 division. This zero reading and all subsequent data should be recorded on the data sheet (follow the style of the sample data sheet shown).

EXPERIMENT NO. 1 TESTING MACHINES AND THEIR USE

Calibration of Testing Machine Number____________

Name____________________________ Date__________

Proving Ring Micrometer Readings or Weights on Proving Levers			Ring Factor [1]	Correct Load [2] Pounds	Load Indicated by Testing Machine	Error [3]		Sensitiveness	
Initial	Final	Difference				Pounds	Per cent	Pounds	Per cent

[1] To be obtained from the calibtration curve for the ring used. In the case of proving levers the ring factor is the multiplication ratio for the levers, usually, 10, and is the same for all loads.

[2] Difference x Ring Factor. = Correct Load.

[3] Error should be indicated as plus or minus. Thus, if the load indicated by the testing machine is less than the correct load, the error is minus.

Apply a small load and oscillate the ring by hand. Continue this movement while slowly increasing the load, until the friction is too great to allow for the movement by hand. Increase the load until the lowest calibrating load to be applied is reached. Observe the micrometer dial reading and the load indicated by the testing machine. The difference in initial and final ring readings times the ring factor furnished by the calibration curve is the correct load and should be recorded on the data sheet. The error is the indicated load minus the correct load and should be given as plus or minus. Remove the load and check the initial zero load reading of the dial. Repeat this procedure for each load to be applied. Repeating the zero load reading permits a continuous check on variation due to change in temperature.

Most elastic proving rings are calibrated at 70° F. When used at any other temperature correction should be made with the following formula:

$$d_t = \frac{d_{70}}{1 + K(t - 70)}$$

in which d_t = deflection of ring as indicated by micrometer dial reading at existing temperature, t.

d_{70} = deflection of ring at 70° F.

K = a coefficient depending upon the composition and heat treatment of the ring. An average value of K is -0.00015 per degree Fahrenheit. The correct value, if other than this, will be given by the instructor.

The sensitivity of the testing machine, regardless of type, may be found by adding dead weights to the weighing table or lower platen when load is on the calibrating device. The smallest weight in pounds which will cause a perceptible movement of the weighing beam is the sensitivity in pounds at that load. It may also be expressed as a percentage of the applied load.

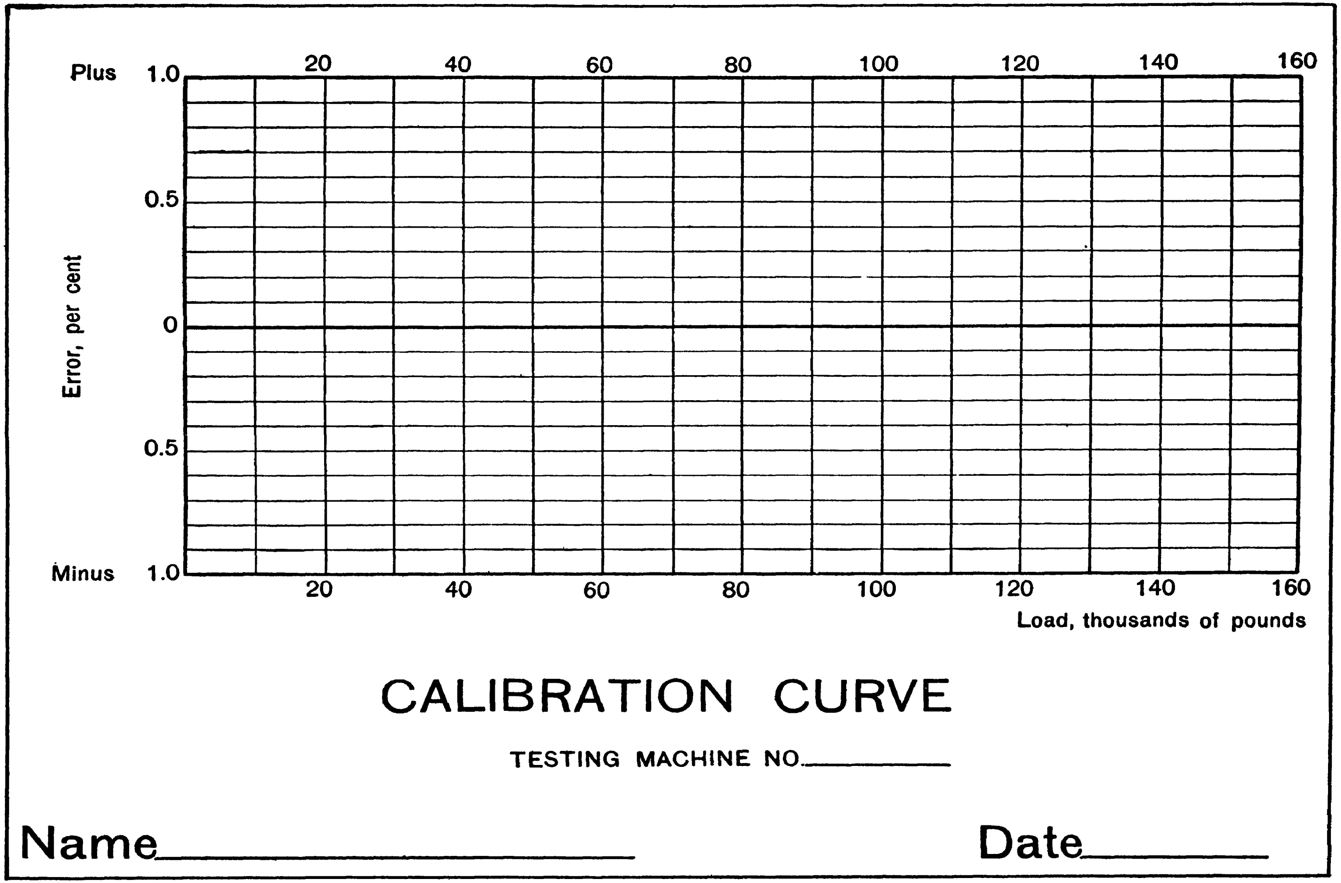
Preparation of Report

CALIBRATION CURVE

Draw the calibration curve by plotting the error observed at each load. Follow the form used for the sample curve sheet. Connect the plotted points by straight lines.

DISCUSSION

1. What are the main wearing surfaces in the testing machine studied? Which of these influence the accuracy and sensitivity of the machine?
2. Why is it necessary to center the specimen on the weighing table?
3. Why are the weighing and loading systems separate?
4. For vertical type testing machines, in what direction does the head move for a compression and for a tension test? Explain any difference or similarity.
5. A universal testing machine is calibrated in compression over a range of loads from 10,000 to 100,000 lb. and found to be satisfactory. Is it satisfactory for tension tests and for what range of loads might it be used? Explain.
6. A specimen exactly 1 sq. in. in cross-sectional area is required to have a tensile strength of 60,000 psi. but only withstands a maximum load of 59,640 lb. Can it be correctly rejected? Explain.



CALIBRATION CURVE

TESTING MACHINE NO.__________

Name____________________ Date__________

Sample sheet for plotting calibration curve of testing machine in Experiment 1. Coordinate scale shown for load may be modified to conform to the capacity of machine calibrated.

EXPERIMENT 2

THE STRESS-STRAIN DIAGRAM FOR MILD STEEL

One of the most important tools available to the designer of mechanical parts, or machines to make those parts, is a stress-strain diagram of the material to be used. A complete stress-strain diagram is a record of a material's stiffness, limit of elastic action, range and rate of plastic action, elastic or fracture energy absorbing ability, and ultimate breaking strength. In the selection of metals for hydraulic presses, stamping machinery, and other metal working equipment, a knowledge of these properties of the material to be worked is invaluable. For most mechanical parts designed for static load-carrying ability and not employing previously untested materials, the complete stress-strain diagram is not necessary and the design may be carried out in the usual manner using routine test results. In the case of most metals, the modulus of elasticity of which is not changed appreciably by heat treatment, cold working, or mild alloying, the stress-strain diagram is not necessary except for the determination of the proportional elastic limit or the yield strength. This experiment will be devoted principally to those properties of the stress-strain diagram which are helpful in studying metal working problems, together with some energy determinations and other practical applications that are directly obtainable from the diagram.

A tension test subjects a metallic specimen to similar conditions of metal working which are encountered in cold-drawing, forming, straightening, and similar operations. Likewise, the compression test simulates many of the conditions encountered in stamping, pressing, and forging. A stress-strain diagram of the material for the conditions of use would then be very helpful in forecasting the action of the part being formed by the metal working operation. The unit stress and consequently the total pressure required to stretch any sized piece may be determined beforehand from the stress-strain diagram. Since the area under the curve at the unit stress or total deformation desired is the energy which must be expended by the metal working equipment, the design of such equipment may be aided by a knowledge of the behavior of the material which it is to form. Thus the stress-strain diagram provides data for working the material and also for designing the machines to do this work.

It is the purpose of this experiment to acquaint the student with the manner in which stress-strain data are obtained, the apparatus used for measuring strain, the method of presenting this data in the form of a stress-strain diagram, and the interpretation of that diagram to obtain certain physical properties as well as applications to metal working problems.

Extensometers

In order to obtain the data for the stress-strain diagram it is necessary to make use of a strain measuring device commonly called an *extensometer* (for extension meter). The component parts of such an instrument are shown in Figure 29. It is necessary that the dial gages read to 0.0001 in. Extensometers are made in which micrometer lead screws and attached dials coupled with electrical type contacts are used to measure the change in length. As the specimen stretches, the upper and lower collars move with respect to one another and this movement is indicated by the gages. Extensometers of this type require two dials as shown to yield a correct average strain. The more modern gages measure strain with reference to two knife edges. A gage of this type is shown in Figures 30(a) and (b). The fixed knife edge is rigidly mounted in the frame of the extensometer

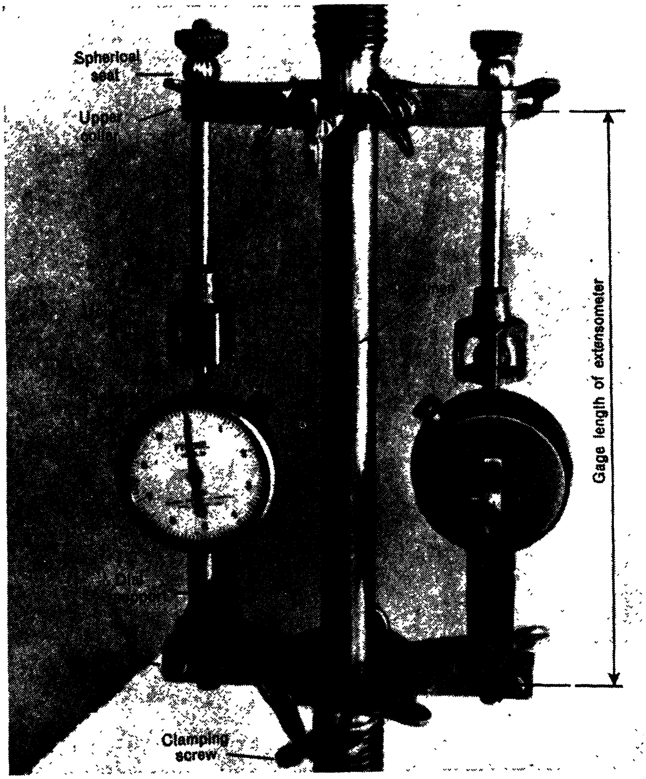


Fig. 29. Principal parts of an extensometer. Two dials provide correct average strain. Knife edges may be substituted for the clamping screws.

and is considered as a fixed reference point. As the specimen is strained the movable knife edge pivots about a fulcrum in the extensometer frame and bears against the stem of the dial gage to indicate elongation. An adjusting screw permits the dial hand to be adjusted to zero and for maximum travel at the beginning of the test.

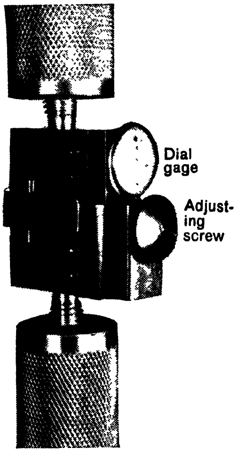


Fig. 30(a). Olsen 2-in. extensometer attached to specimen.

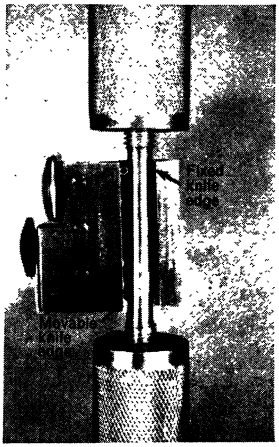


Fig. 30(b). Olsen 2-in. extensometer. Side view showing fixed and movable knife edges. Movable knife edge extension (dotted) bears against dial stem. Springs in frame of extensometer hold knife edges against specimen.

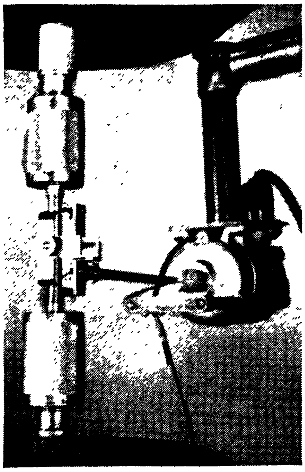


Fig. 31. Templin-type electrical extensometer in place on tension specimen. Selsyn motor in background.

When many routine tests are being made, and only the yield strength is determined from the stress-strain diagram, it is advantageous to use the

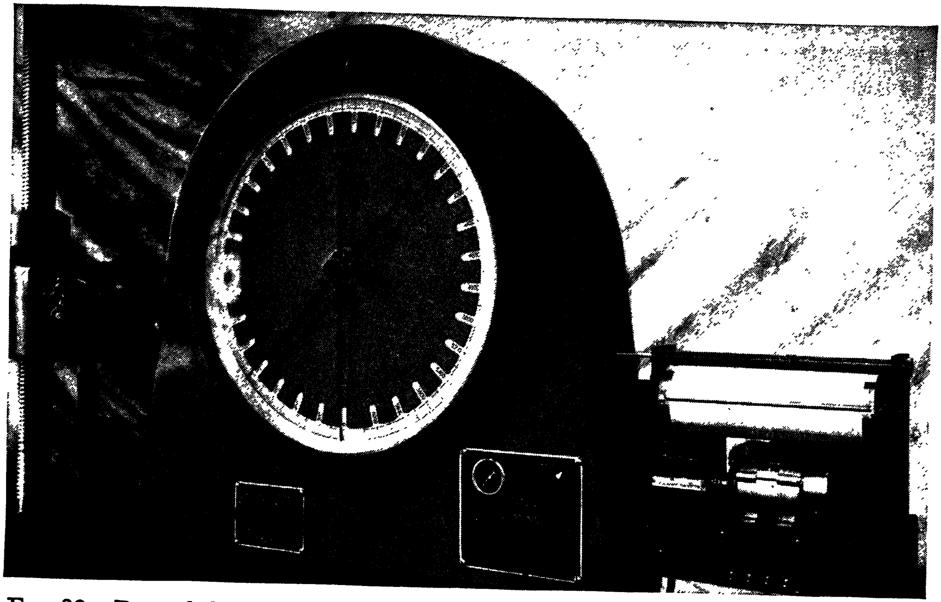


Fig. 32. Record drum actuated by Selsyn motor (*below*) coupled with Templin-type electrical extensometer shown in Figure 31. Load is indicated by a pen moved horizontally by the rod shown emerging from the control head. (Courtesy Baldwin-Southwark)

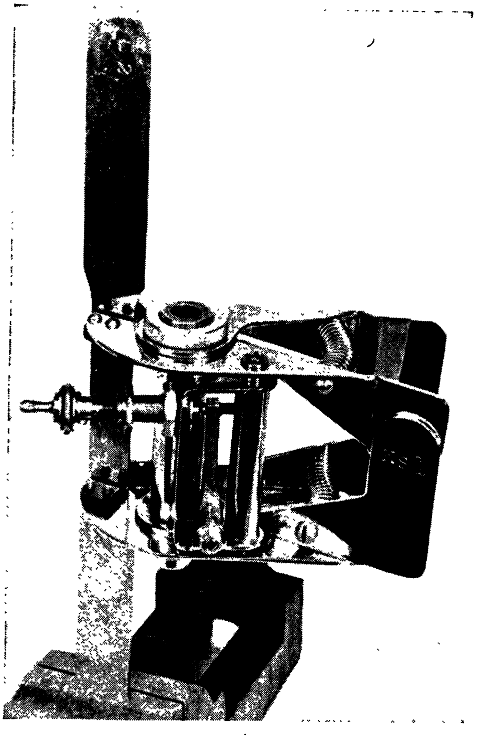


Fig. 33(a). Kenyon-Burns-Young electrically operated extensometer attached to sheet metal specimen. (Courtesy Baldwin-Southwark) autographic extensometer. Such an extensometer automatically records the strain and, when coupled with a suitable load-indicating device from the loading system of the testing machine, may be used to draw automatically a load-elongation diagram from which the yield strength may be determined. The record drum must be rotated to indicate strain. This may be done with a string or wire system from the crosshead of the testing machine or from an actual extensometer attached to the specimen.

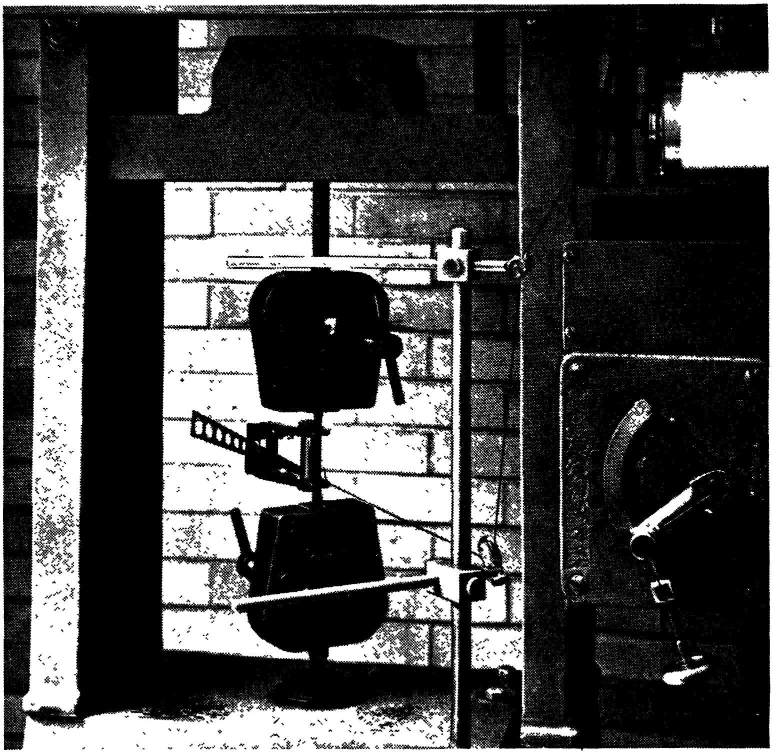


Fig. 33(b). • Kenyon-Burns-Young string-operated extensometer attached to sheet metal specimen. Autographic drum may be seen at upper right. (Courtesy Baldwin-Southwark)

A more rapid method better adaptable to routine testing is to employ the electrical extensometer. Such an instrument is shown in Figure 31. The gage itself is merely a mechanical lever but as it is displaced by the strain in the specimen the displacement is followed with the aid of electrical contact points. Two Selsyn synchronous motors are used, one for the extensometer and one for the record drum. As the Selsyn motor attached to the extensometer follows the lever displacement, the motor coupled with it and attached to the record drum indicates this amount of follow by turning the record drum and indicating strain. The record drum with its Selsyn motor is shown in Figure 32. With this type of equipment it is possible to test a specimen and obtain its load-elongation diagram in less than 5 minutes.

Other types of extensometers are shown in Figures 33(a), 33(b), 34, and 35. Most extensometers now use the more popular 2-in. gage length, although some are adaptable to gage lengths of from 2 to 8 in.

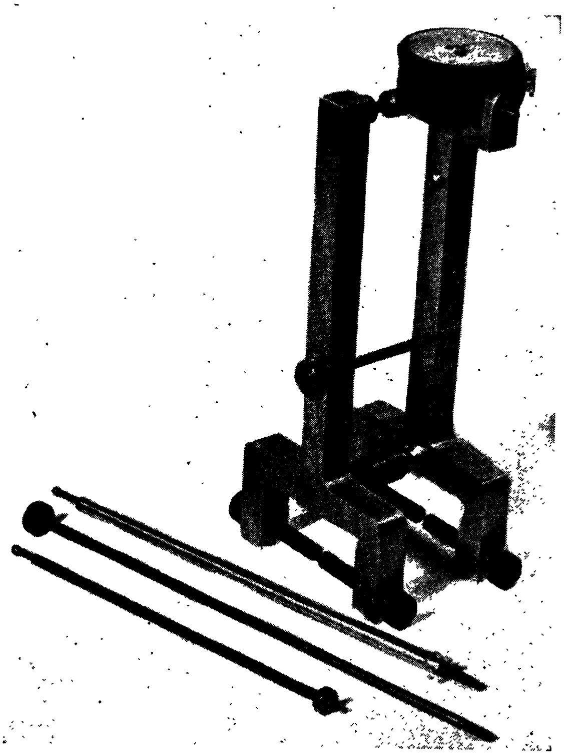


FIG. 34. H. F. Moore type of extensometer adaptable to different gage lengths. (Courtesy Baldwin-Southwark)

EXPERIMENTAL PROCEDURE

Extensometer Tension Test

APPARATUS—A universal testing machine of sufficient capacity for the specimen tested, spherically seated tension bolts, flat and pointed micrometers, extensometer, 12-in. scale, dividers, gage punch, and hammer.

MATERIAL—Mild steel of structural grade, 0.15 to 0.25 per cent carbon. (Refer to A.S.T.M. Designation E8-40T, or later, for standard specimen sizes.)

Obtain the dimensions of the specimen and record them on the data sheet. Place punch marks at 1-in. intervals over the entire gage length. Examine the extensometer carefully and note the equivalent, in inches, of each dial division. The specimen should be held in spherically seated tension bolts during the test. These tension bolts, as shown in Figure

36, permit an axial load to be applied to the specimen in spite of a bent specimen or unaligned crossheads on the testing machine. The extensometer may be mounted on the specimen before or after placing it in the

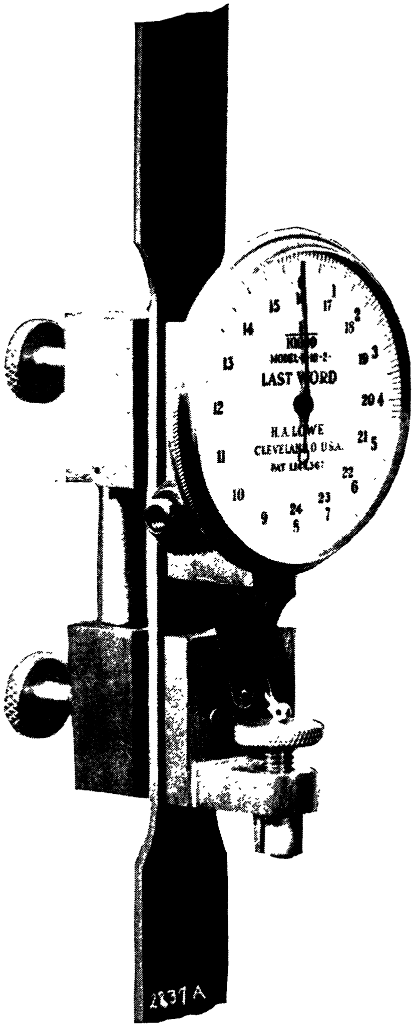


FIG. 35. Tripolitis sheet metal extensometer. (Courtesy Baldwin-Southwark)

tension bolts, depending upon the type. The testing machine should be balanced before the tension bolts are drawn tight.

Apply a small initial load to the specimen to seat the tension bolts properly and take up any slack in the extensometer. The extensometer dial or dials should then be set to zero or an initial reading taken.* In-

* Setting the extensometer dials to zero when an initial load is on the specimen yields a set of data from which the stress-strain diagram obtained will not pass through zero-zero. This is accounted for in the "correction to zero" by which the average movement of the dial for the amount of the initial load is determined from the data and added to each reading or

crease the load in such increments that the increment of stress is 4000 or 5000 psi., noting the dial readings at each load. Since stress is proportional to strain within the proportional elastic limit, the increment of total strain (difference between average dial readings) for each increment of load should be approximately constant within that range. When the increments of total strain start to increase, the proportional elastic limit has been passed and the loading increments should be reduced so that the increment of stress is between 500 and 750 psi. When the yield point is reached, the specimen will stretch very rapidly, the extensometer will "race," and the load will drop off. In general, most extensometers do not permit sufficient total elongation to be measured to obtain data very far into the plastic range. The extensometer should, therefore, be removed when near the limit of its travel. This is usually just after the yield point is reached. The reduced load and the accompanying strain should be recorded in order to show this yielding action on the stress-strain diagram.

EXPERIMENT NO. 2 EXTENSOMETER TENSION TEST OF MILD STEEL

Extensometer______________________

Name______________________________ Date______________

Machine Loads		Dial Readings, Divisions				Elongations		Diameter at this load	Area at this load	True unit stress psi.
Total lb.	Unit stress psi.	1	2	Average	Corrected to zero	Total in.	Unit in./in.			

Original diameter =
Original area =
Gage length of extensometer =

Final diameter =
Final area =
Elongation in 8 in. =
Elongation in 2 in. =

Distance between each punch mark after specimen breaks.

1______ 2______ 3______ 4______ 5______ 6______ 7______ 8______

Type of fracture ______________________

When the extensometer is removed the load on the specimen should be increased until the ultimate is reached. Up to this point the material stretches uniformly over its entire gage length. This observation is important and should be checked with the aid of dividers placed over each inch of the gage length. Only when the ultimate load is reached does one particular part of the specimen stretch very rapidly to produce localized yielding and subsequent fracture. If it were not for this fact it would be

average of readings. Thus the data is corrected to an equivalent condition as though the strain had actually been measured from zero stress. This gives a stress-strain diagram which is straight and does not "broom out" or become flat near the origin.

impossible to work metals by drawing, forming, stretching, etc., since the deformation would not be uniform and therefore un-uniform thickness, varying physical properties (due to cold-working), or actual breakage might occur. That the material does stretch uniformly up to the ultimate load may be seen from Figures 37(a) and (b).

The localized yielding occurring beyond the ultimate load causes a reduction in area at the point of subsequent fracture and a consequent reduction in load. This reduced load is of no interest unless the true stress-strain diagram is to be obtained. Record the maximum load, break the specimen, and examine the type of fracture (refer to Figure 13). Secure the reduced diameter at the "neck" of the fracture and the elongation over every inch of gage length.

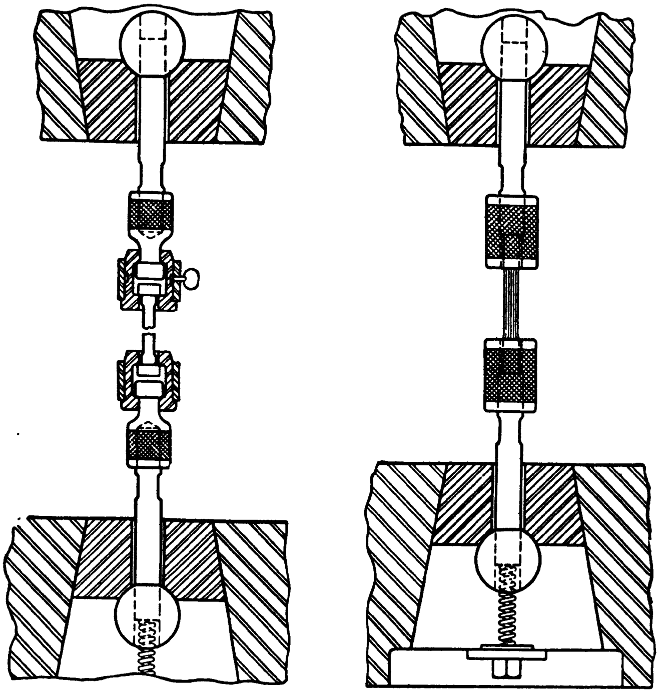


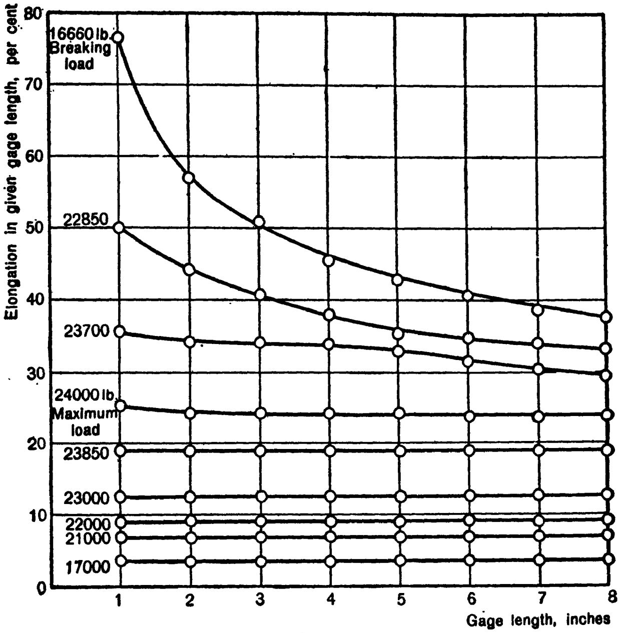
FIG. 36. Spherically seated tension bolts for threaded end specimens (*right*) and shoulder end specimens (*left*). Shouldered end specimens are usually used for cast or very hard materials. (Courtesy Baldwin-Southwark)

If the true stress-strain diagram is to be plotted, the diameters at various loads in the plastic range up to the actual breaking point should be observed.

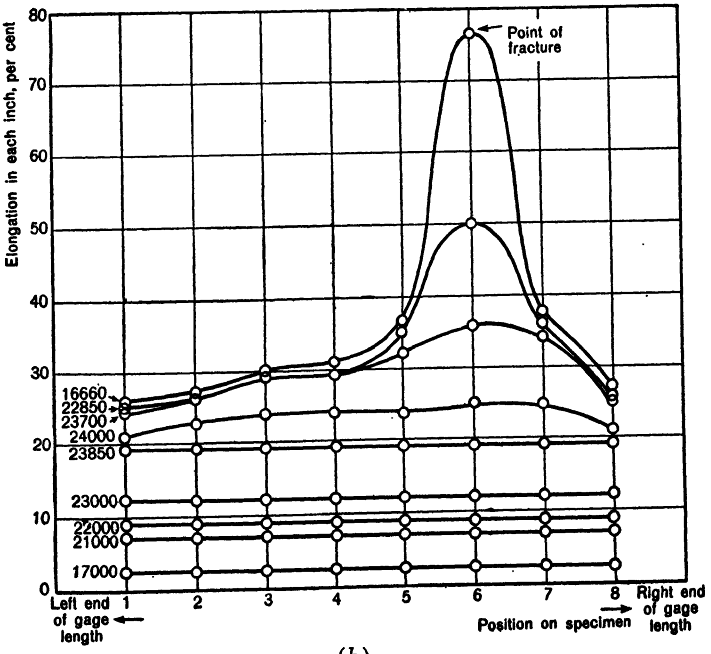
PREPARATION OF REPORT

STRESS-STRAIN DIAGRAM

After the observed data have been converted to stress and strain, the diagram showing the relationship between the two should be plotted on cross-section paper

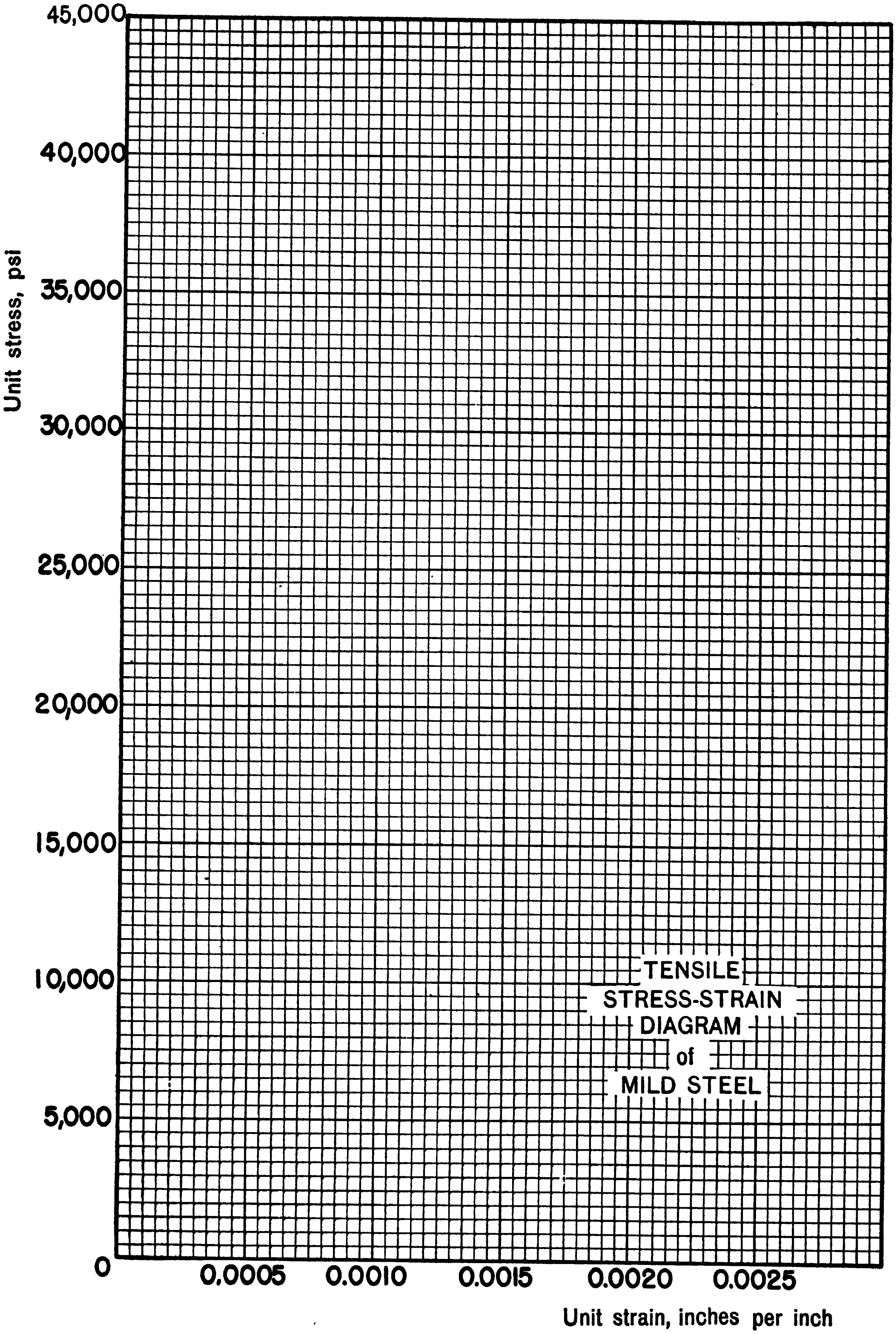


(*a*)

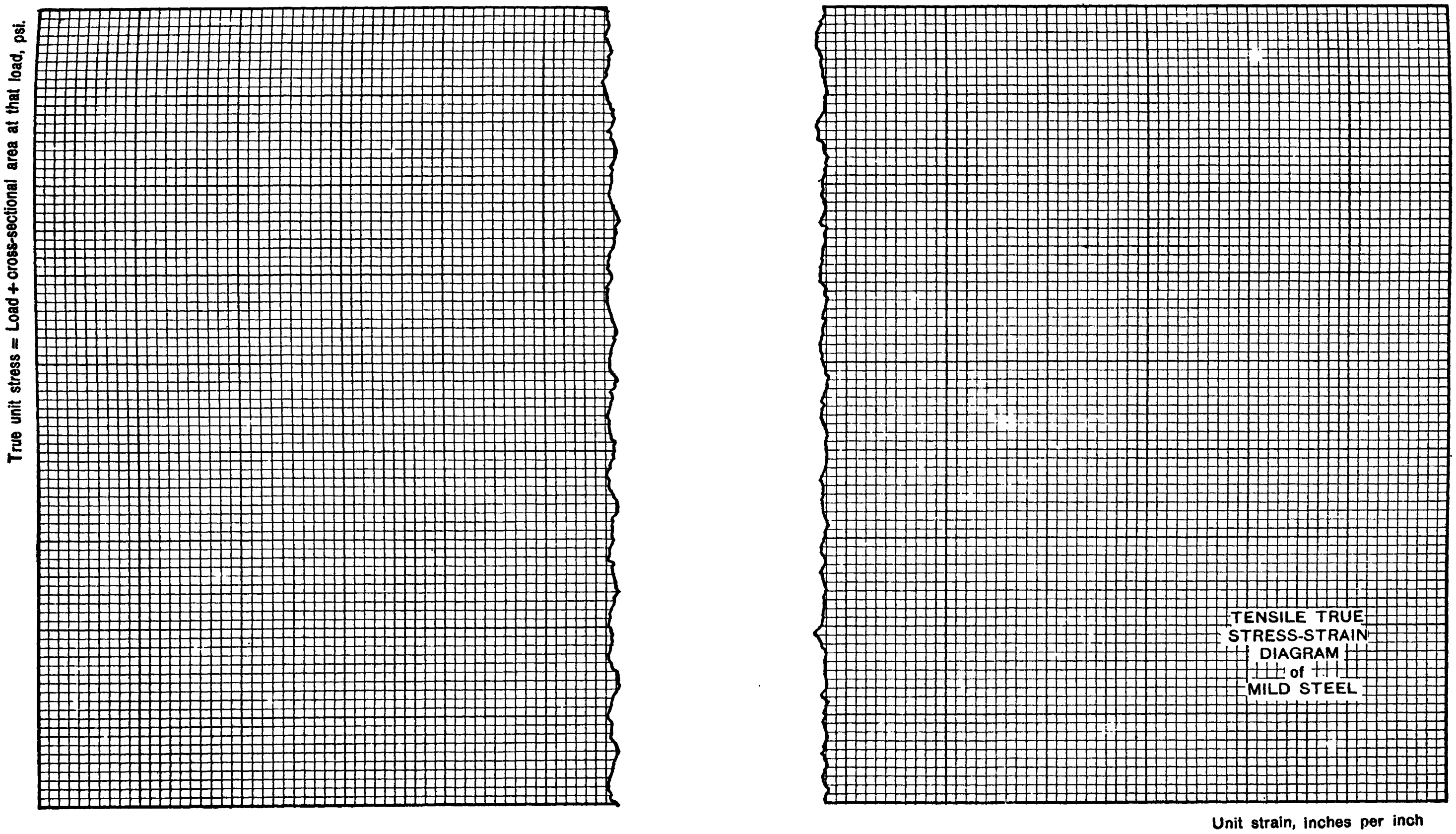


(*b*)

FIGS. 37(a) and (b). Percentage elongation for various gage lengths at loads indicated to left of curves. Data show that specimen (0.75-in. diameter mild steel) stretched uniformly over entire length up to maximum load and then began to yield rapidly at the point which subsequently fractured.



Sample sheet of cross-section paper for stress-strain diagram in Experiment 2, showing coordinate scales.



Sample sheet of cross-section paper for true stress-strain diagram in Experiment 2. Abscissa coordinate should be about 15 in. long and scales for both coordinates should be selected and filled in. Scales selected should give the most effective plot of the data.

similar to the sample shown. Follow the instructions previously given for plotting the data.

If the true stress-strain diagram is to be plotted this should be done on a long sheet of cross-section paper. Select units for the coordinate scales so that the plastic portion of the diagram occupies most of the graph sheet.

When required to do so, give a summary of the test results on all curve sheets.

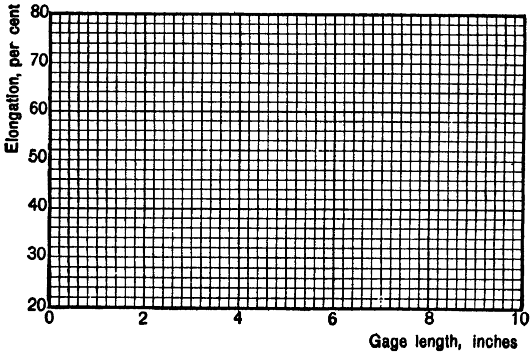
COMPUTATIONS

From the data or curve sheet compute results for the following items, giving numerical examples and stating units for each result:

1. Unit stress at proportional elastic limit from curve.
2. Unit stress at yield point.
3. Tensile strength.
4. Elongation.
5. Reduction in area.
6. Modulus of elasticity.
7. Modulus of elastic resilience.
8. Elastic ratio.
9. Correction to zero.

DISCUSSION

1. What does the type of fracture tell about the material in the specimen?
2. On a curve sheet similar to that shown plot the percentage elongation for 1, 2, 4, 6, and 8 in. against the gage length. Does the relationship obtained explain why it is necessary to state the gage length when reporting elongation? Explain.



Coordinate scales to show effect of gage length on percentage elongation.

3. In the following table compare the test results with the A.S.T.M. specification governing the type of steel tested.

	Test results	A.S.T.M. Specification *	Does specimen pass or fail this requirement?
Stress at yield point, psi.			
Tensile strength, psi.			
Elongation, per cent			

* A.S.T.M. Designation ....

Would this material be accepted?

4. Why is the term "yield point" a misnomer?

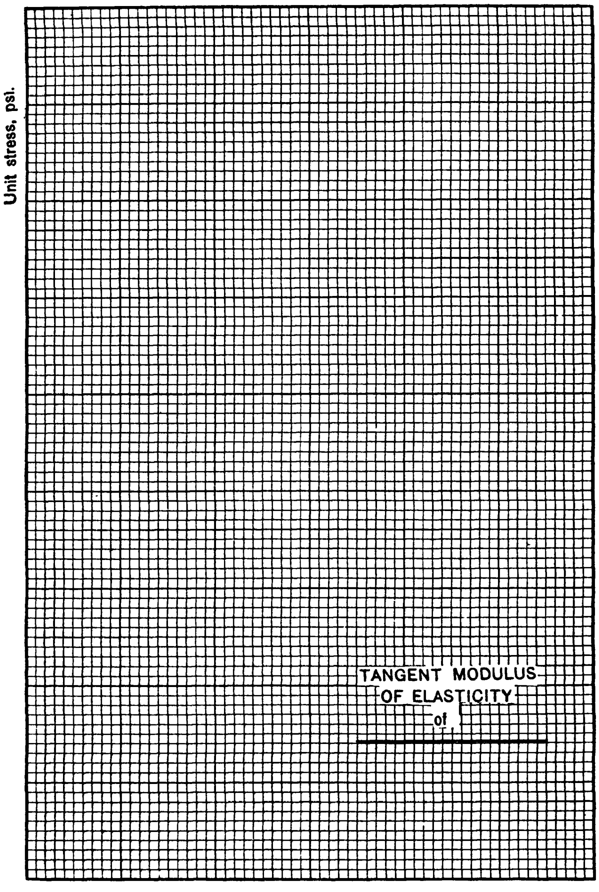
Application of the Stress-Strain Diagram

TANGENT MODULUS—The slope of the stress-strain diagram (modulus of elasticity) is constant in the elastic range but decreases with increased stress in the plastic range. This may be shown by drawing tangents to the diagram at various stresses and calculating their slopes. The slope of each tangent is the tangent modulus of elasticity at that stress (the tangent modulus has no significance without a statement of the stress at which it was obtained). Many applications of the tangent modulus may be made in problems of elastic stability or in the design of metal forming equipment. Since the stiffness of a material constantly decreases in the plastic range, the stress-tangent modulus diagram will aid in the determination of a point in a metal working operation, for example, where the operation may be speeded up by virtue of this decreased stiffness.

From the stress-strain diagram previously plotted determine the tangent modulus at various stresses and plot the stress-tangent modulus diagram on cross-section paper following the sample curve sheet shown. Refer to Figure 9 if necessary.

METAL WORKING—In the stress-strain diagram, as explained previously, the area under the diagram is a measure of total energy expended at any stress or amount of strain, and therefore has many applications in metal working problems. When a metal is worked at a condition of considerable distortion, it is being stressed far out in the plastic range and the ordinary stress-strain diagram will not give a true picture of the energy required for such working. In such a case it is necessary to use the true stress-strain diagram.

In Figure 38 is shown a plate stretcher used to impart a specified amount of cold working * to metal sheets or plates and at the same time to make them flat. Much of the design of such a machine depends upon the material to be used in it. The student should follow through the computations required below using the stress-strain relationships previously plotted.



Sample sheet of cross-section paper for tangent modulus of elasticity in Experiment 2. Suitable scales that will most effectively show the data should be chosen and filled in for both coordinate axes.

---

* Cold working is a process of working a metal at a temperature where it is metallurgically "cold" (no changes of metallurgical structure). When the metal is worked in its plastic range, it is deformed inelastically due to slip of the grains of the metal. This slipping makes the material stronger due to slip interference or keying of the grains during the working operation. Referring to Fig. 7(a) it may be seen that if the load is again increased after the cycle of loading and unloading shown, the stress-strain relationship will then follow the line *AB*. At the point *B* the curve's general trend will again be resumed. For this second diagram the proportional elastic limit and yield strength would both be increased.

Problem. Given a plate .... in. long, ... in. wide, and .... in. thick of the same material as tested in this experiment, determine the total force required to cold work this plate a specified amount, the distance the movable jaw must move during this operation, and the horsepower required to complete the operation in a specified time.

Total Force. It is required that the plate be cold worked to a unit stress of .... psi. What total force must be exerted by the hydraulic system to fulfill this requirement?

Total Movement of Jaw. If a pressure gage is not available to enable the operator of the stretcher to know when the specified stress has been reached, a dial may be attached to the movable jaw to give the same result.

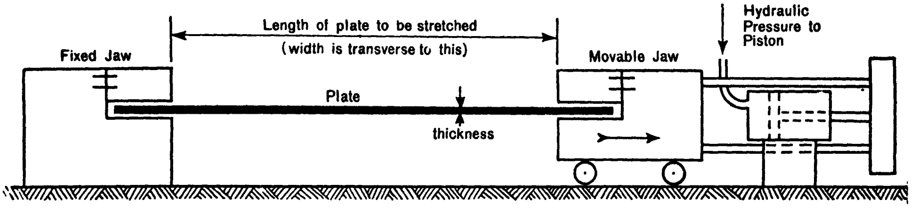

Length of plate to be stretched
(width is transverse to this)
Fixed Jaw
Movable Jaw
Hydraulic Pressure to Piston
Plate
thickness

FIG. 38. Plate stretcher used to flatten metal sheets and plates and to impart a specified amount of cold working.

It is specified that the plate be stretched to a point where the permanent set (cold working) is .... per cent. Through what distance must the movable jaw travel to fulfill this requirement? (Remember that the material springs back some after release of load.)

Horsepower Required. By counting the squares under the stress-strain diagram and converting these squares to energy expended, on the basis of the scales used, it is possible to determine the total energy required to deform the plate a specified amount. When this energy must be expended in a certain time, the horsepower may be calculated.

It is specified that the plate be stretched to a point where the permanent set (cold working) is .... per cent and that this stretching be accomplished in .... seconds. Determine the horsepower required to accomplish this. No factor of safety need be used.

(a) Total energy as the area under the stress-strain diagram at the specified permanent set. .... in.-lb. per cu. in.

(b) Total energy required for the plate. .... in.-lb.

(c) Horsepower required to complete operation in .... seconds. (One horsepower is equivalent to 550 ft.-lb. per second.)

EXPERIMENT 3

THE EFFECT OF CARBON CONTENT UPON THE PROPERTIES OF STEEL

The amount of carbon is the single element contributing most to the physical properties of unalloyed steels. Steel is actually an alloy of carbon and iron (theoretically pure iron and not cast iron). Other elements present cannot feasibly be removed, or are helpful to the properties of the steel. These additional elements are manganese, phosphorus, and sulfur.

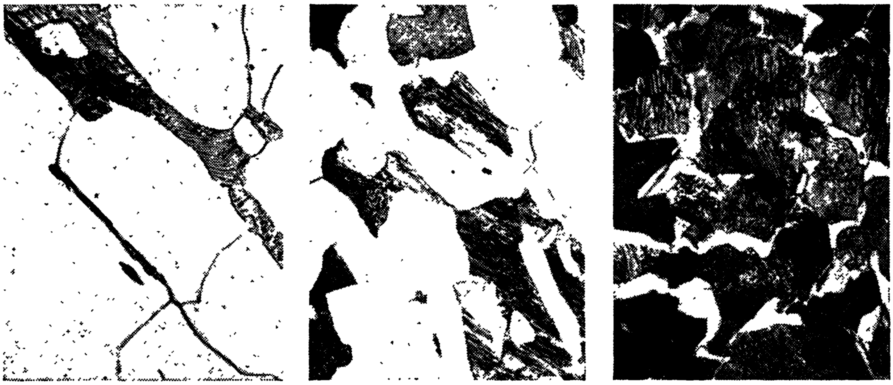


Fig. 39. Increase in quantity of pearlite in plain carbon steel. From left to right 0.10, 0.30, and 0.60 per cent carbon, all at 250×. Large light areas are grains of ferrite matrix. In pearlite grains, bright lines indicate cementite and dark lines ferrite due to fact that cementite is not affected by etching solution and stands in relief. Softer ferrite is depressed by polishing and tarnished by etch so that it is in shadow and appears dark.

When carbon is alloyed with iron, it combines chemically in the ratio of 1 part carbon to about 15 parts of iron and thereby forms iron carbide, a constituent of steel, which is called *cementitc.* This is the hardest constituent in the steel, and the quantity of it therefore contributes greatly to the final tensile strength and hardness. When steel is cooled to room temperature, internal changes of form take place and the final structure consists of iron and cementite mechanically mixed together to form a constituent named *pearlite,* the pearlite being suspended in a matrix of ferrite. Since the pearlite is a mechanical mixture of iron and cementite it possesses properties intermediate between each of them. The addition of the soft iron is equivalent to reducing the hardness and strength of the cementite and increasing its ductility. As the carbon content of a steel is increased, the amount of pearlite present also increases and the physical properties are changed accordingly. In Figure 39 is shown a series of photomicrographs illustrating the increase in quantity of pearlite in a steel as the carbon content is increased. Pearlite is composed of approximately 0.9 per cent carbon.

While the primary intent of this experiment is to illustrate the effect of carbon upon the strength, hardness, and ductility of steel the student will also become familiar with the routine manner in which tension tests are made commercially. The acceptance test for steel is made to check fulfillment of specification requirements for tensile strength, yield point, elongation, and reduction of area, and is often termed the "four-point test." Since the modulus of elasticity and yield strength need not be determined, no extensometer readings are required and the test may be performed in a relatively short period of time.

EXPERIMENT NO. 3

EFFECT OF CARBON CONTENT

Name ______________________ Date ____________

Specimen Number		1	2	3
Carbon, per cent				
Manganese, per cent				
Phosphorus, per cent				
Sulfur, per cent				
Original diameter, in.				
Original area, sq. in.				
Load at yield point, lb.	By beam drop			
	By dividers			
	By scaling			
Stress at yield point (Beam drop), psi.				
Maximum load, lb.				
Tensile strength, psi.				
Elongation in 2 in.		in.	in.	in.
		per cent	per cent	per cent
Elongation in 8 in.		in.	in.	in.
		per cent	per cent	per cent
Final diameter, in.				
Final area, sq. in.				
Reduction in area, per cent				
Elastic ratio, per cent				
Fracture type				
Rockwell B hardness				

Experimental Procedure

APPARATUS—A universal testing machine of sufficient capacity for the size of specimen tested, Rockwell type of hardness tester, flat and pointed micrometers, 12-in. scale, dividers, gage punch, and hammer.

MATERIAL—Steel specimens containing approximately equal amounts of manganese, phosphorus, and sulfur but with carbon content varying from low to high. It is preferred that three steels be used within the range of structural, intermediate, and hard grades conforming to A.S.T.M. Designation A15-39, or later.

The instructor will demonstrate the proper method of performing a commercial tension test of steel and will then distribute test specimens to each squad. Determine the hardness of each specimen with the Rockwell tester, using the B scale. Refer to Experiment 11 for the manner of conducing the hardness test. Secure the chemical analysis of each specimen. Measure the diameter of each specimen at three positions along the length, taking two measurements perpendicular to each other at each position. Record the average diameter.* With the gage punch lay off marks at 1-in. intervals along the entire center section of the specimen and to within 4 in. of each end.

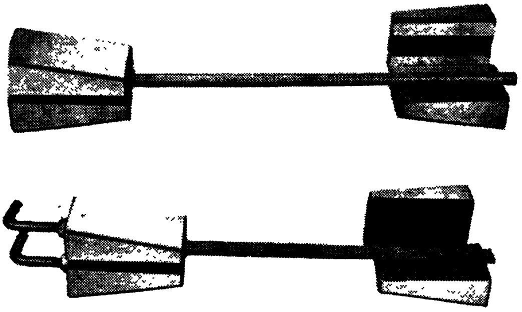


Fig. 40. Wedge type grips to hold round (*above*) and flat (*below*) specimens in tension.

Wedge type grips with which to hold round or flat specimens are shown in Figure 40. Insert the specimen in the wedge grips so that it is held over the entire length of grip. Liners should be used to keep grips within their slots in the crossheads. Apply load at a moderately high rate of speed (15,000 psi. per minute is satisfactory) until 0.8 of the anticipated yield point load is reached. Reduce the speed to slow until the yield point is reached. Determine the yield point by the drop of beam, dividers, and fall of mill scale. Again increase the speed to a moderately high value † and obtain the maximum load. It should be noted and clearly understood that it is only when the scale beam is in floating balance that the position of the poise on the scale beam has any significance whatsoever.

After the specimen has fractured, the broken pieces should be placed together and the reduced diameter, elongation in 8 in., and elongation in

---

* Cross-sectional areas may be secured from the area table in the Appendix.

† In the plastic range the testing speed will be governed by the rate of strain and not the rate of stress increase.

2 in. obtained. Note the type of fracture for each specimen. With a hacksaw, cut each specimen partly through at the grip end and break the section completely with the aid of a hammer. Note the following significant differences in color and texture:

Low carbon specimen—Dull gray in color, indicating large grain size and therefore low strength but high ductility.

Medium carbon specimen—Brighter gray in color, indicating finer grain size, higher tensile strength, and less ductility.

High carbon specimen—Bright shiny gray in color, indicating finest grain size of all three specimens, highest strength, and least ductility.

Figure 41 shows the characteristic appearance of the specimens after fracture. The relative ductilities are apparent from this figure.

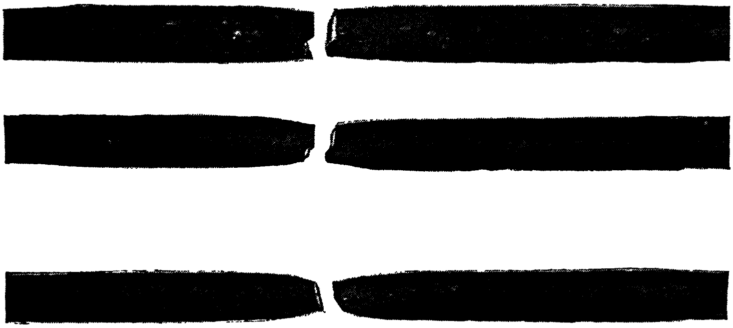


Fig. 41. Variation in ductility of various carbon steels (0.10, 0.30, and 0.60 per cent carbon) as evidenced by reduction in area. High carbon specimen at top.

Preparation of Report

COMPUTATIONS

From the data compute the following results, giving numerical examples for only one specimen and stating the units for each result:

1. Stress at yield point.*
2. Tensile strength.
3. Elongation.
4. Reduction in area.†
5. Elastic ratio.
6. Using the tensile strength as a satisfactory average true stress throughout the plastic range, and the final elongation in the given gage length as a satisfactory average strain, determine the fracture energy, in in.-lb. per cu. in., which each specimen exhibited. This is an approximate value and should be used for comparative purposes only. For more exact results the method outlined in Experiment 2 should be followed.

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* Any sample calculations which have been given in previous computations need not be repeated but may be itemized if desired.

† Percentage reduction in area may conveniently be obtained from the reduction in area table in the Appendix.

GRAPH SHEET

On cross-section paper similar to the sample shown, plot the following relationships:

1. Carbon content and stress at yield point.
2. Carbon content and tensile strength. Numbers 1 and 2 only to be plotted in the left portion of the sheet.
3. Carbon content and ductility (percentage elongation in 2 in., 8 in., and reduction in area).
4. Carbon content and elastic ratio.
5. Carbon content and Rockwell B hardness.

It should be pointed out that formulas are available with which to calculate tensile strength when the chemical composition of the steel is known. These formulas vary so much for different degrees and conditions of mechanical treatment of the steel that they are usually special cases adaptable only to certain steels and, therefore, will not be discussed here.

DISCUSSION

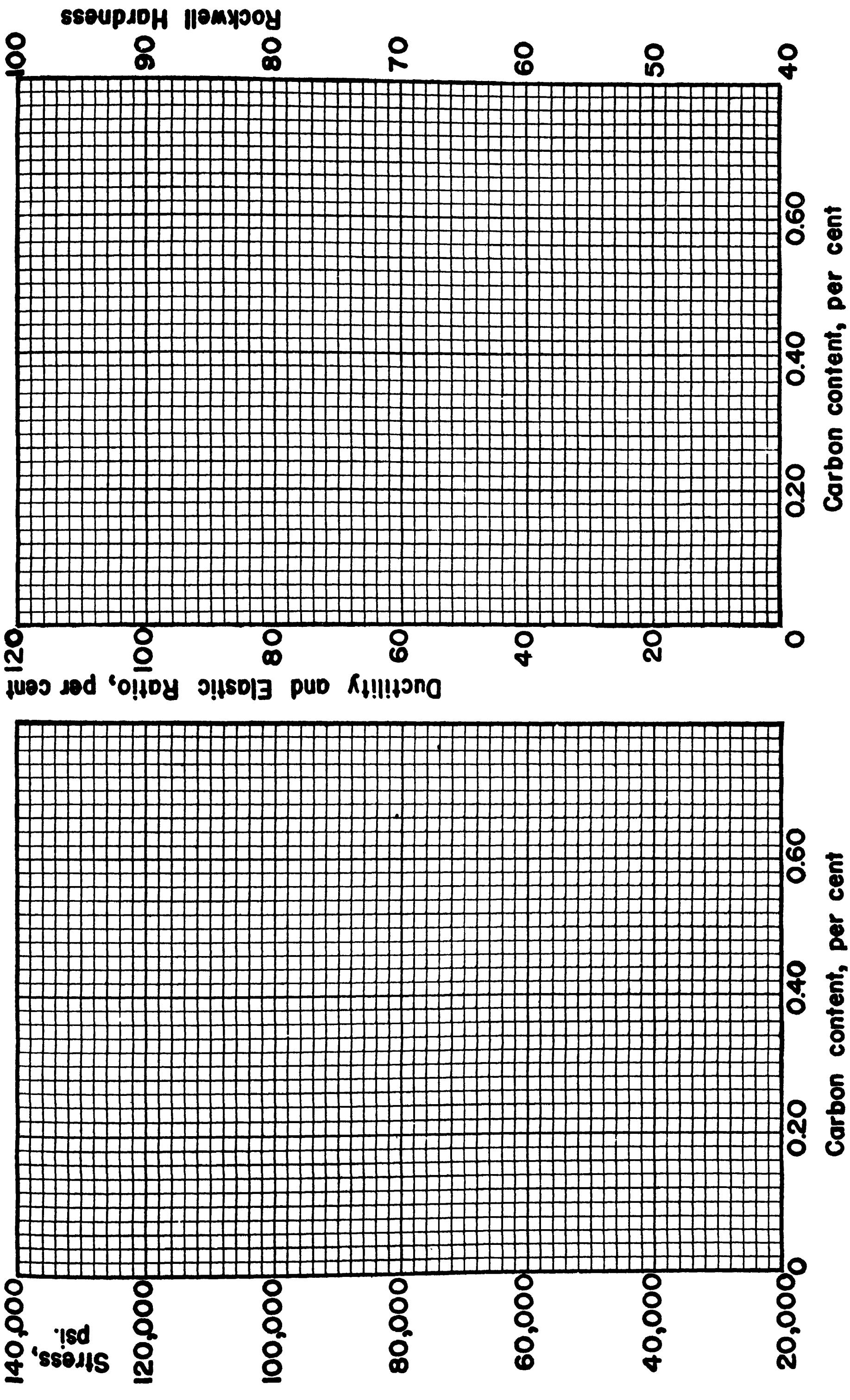
1. In the following table compare the test results with the A.S.T.M. specification governing the type of steel tested.

	Specimen	Tensile strength, psi.	Yield point, psi.	Elongation** per cent	Is specimen accepted?
Test results					
A. S. T. M. Spec.*					
Pass or fail?					
Test results					
A. S. T. M. Spec.*					
Pass or fail?					
Test results					
A. S. T. M. Spec.*					
Pass or fail?					

*** A. S. T. M. Designation______________**

**** Gage length______________in.**

2. What effect would slow annealing (heating the material to the correct temperature and then cooling it slowly to decrease internal stresses and permit larger grain size) have upon the strength, ductility, and hardness of the materials tested?
3. From the relationship of elongation to percentage carbon, as plotted on the graph sheet, it will be noticed that the curves for 2 in. and 8 in. are not parallel. This indicates that, while ductility is reduced with increased carbon, the reduction is much faster in 2 in. than in 8 in. Explain this difference.
4. From the results of computation 6 for fracture energy, which of the materials would be best for an automobile coil spring? Which would be best for a railroad car coupler? Explain in each case.



Sample sheet of cross-section paper for Experiment 3, showing coordinate scales.

EXPERIMENT 4

SHEAR, TENSION, COMPRESSION, AND COLD-BEND TESTS OF METALS

As has been pointed out in connection with Equations (2) and (3), a ductile material may fail in shear in the tension test or in a combination of shear and tension. It has also been mentioned that a ductile material in compression can fail elastically or by such excessive distortion as to be useless, but in no case does actual rupture take place. These facts are worth remembering in engineering design, particularly when heat-treated materials are used and the applied loads are other than unidirectional.

The shearing strength of a material is necessary in the design of parts, such as riveted joints, connecting rod pins, and airplane propellers. When a part is subjected to an axial load the shearing strength may govern the failure in tension if a ductile material is used, or in compression if a brittle material is used. The possibility of failure by shear should always be checked in design work.

A material's ductility, as measured by percentage elongation and reduction in area, will be an aid to determining its ability to be bent and formed during processing. To determine the minimum radius of bend which the material can withstand without cracking, it is necessary to have more than a knowledge of ductility from the tension test and actually to test for this minimum radius of bend by performing a cold-bend test.

The tests performed in this experiment are conducted in a routine manner as followed in commercial inspection tests. In performing them, the student should acquire an understanding of the manner in which such tests are made and a knowledge of the properties for those materials tested.

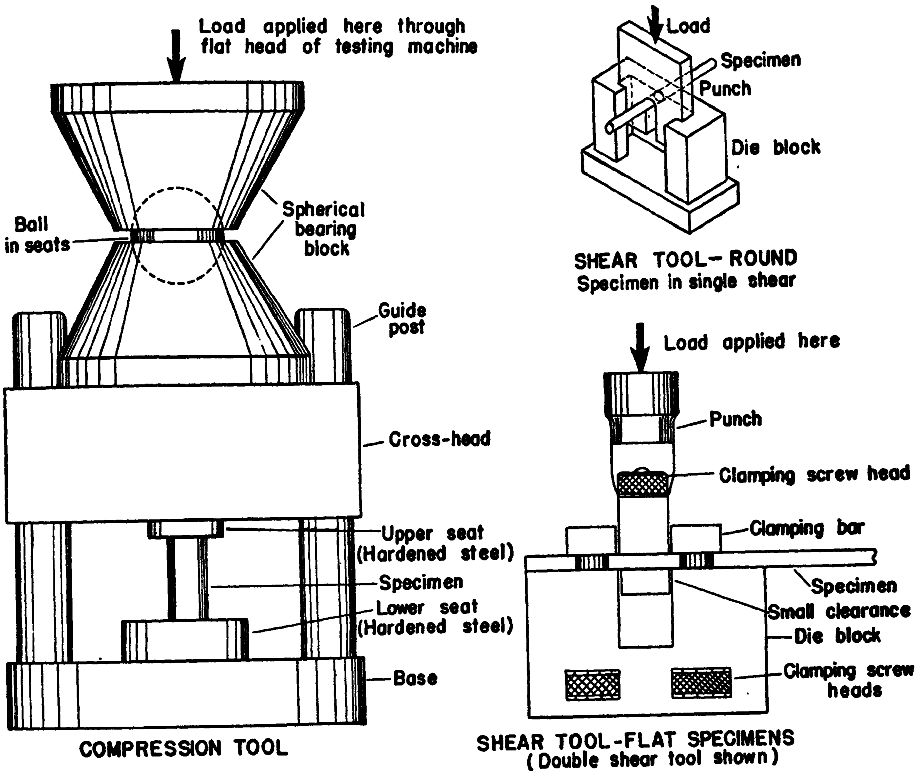
Experimental Procedure

APPARATUS—A universal testing machine, Rockwell type hardness tester, shear tool, compression tool, flat and pointed micrometers, 12-in. scale, dividers, gage punch, and hammer.

MATERIAL—Wrought iron, steel of structural grade, low carbon steel, and flat steel plate of medium carbon content.

Shear Test

As shown in Figures 42 and 43, a shear tool consists of a punch and a die with attachments for clamping the specimen in place and applying load. The specimen may be flat or round and the shearing load may be applied over one or two surfaces, producing single and double shear, respectively. Place the specimen of soft steel in the shear tool and clamp it securely in place with the shear taking place only on the end of the piece. (The remainder of the specimen must be preserved for a subsequent tension test.) With the shear tool centered in place under the loading head of the testing machine, apply load at slow speed until the ultimate is reached. Stop the application of load and note that at this point the punch has not moved far with respect to the die. The movement thus far has been due to actual shear (this will be noted on the fractured specimen as the smooth shiny portion). Re-apply load until the specimen is sheared through. This last cutting action is not shear, but tearing, as may be seen from the fracture.



COMPRESSION TOOL

SHEAR TOOL– ROUND
Specimen in single shear

SHEAR TOOL-FLAT SPECIMENS
(Double shear tool shown)

Fig. 42. Compression and shear tools.

Tension Test

Perform the standard, four-point, commercial tension test, as outlined in Experiment 3, for the wrought iron, structural grade steel, and low carbon steel. Record the test results on the data sheet. Note the difference in fracture of the wrought iron and the other steels due to the composition of the material. Wrought iron consists of low carbon steel with slag mechanically mixed into it. This material was the first workable iron developed, the slag inclusion being a natural result of the melting process in the early furnaces. This direct process for the manufacture of wrought iron has today been supplanted by the indirect method where the slag and refined iron are mixed to form wrought iron. The principal advantage of wrought iron is the ease with which it can be forge welded. Because of its fibrous structure (Figure 44) it is thought by some to have better resistance to fracture impact and corrosion than other steels.

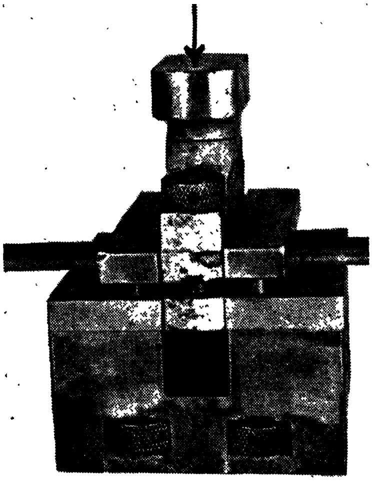
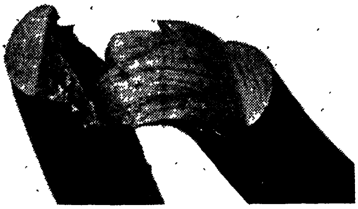


FIG. 43. Flat specimen in shear tool ready for test. Load applied as shown.



FIB. 44. Fibrous appearance of wrought iron fracture.

EXPERIMENT 4

TENSION, COMPRESSION, SHEAR, AND COLD-BEND TESTS OF METALS

Name______________________________ Date________________

TENSION TESTS

Experiment part			
Material and shape			
Original diameter, in.			
Original area, sq. in.			
Load at yield point, lb. **By dividers**			
By drop of beam			
Stress at yield point, psi.			
Maximum load, lb.			
Tensile strength, psi.			
Elongation in 8 inches, in.			
Elongation in 8 inches, per cent			
Dimensions at "neck", in.			
Area at "neck", sq. in.			
Reduction in area, per cent			

COMPRESSION TESTS

Material		
Rockwell hardness before test		
Original length, in.		
Original diameter, in.		
Original area, sq. in.		
Load at yield point, lb. **By scaling**		
By drop of beam		
Stress at yield point, psi.		
Final length, in.		
Final diameter, in.		
Maximum load applied, lb.		
Rockwell hardness after test		

SHEAR TEST

Material____________________
Original dimensions, in.____________
Original area, sq. in______________
Maximum load, lb._______________
Shearing stress, psi_______________

180° COLD-BEND TEST

Material____________________
Edge conditions________________
Dimensions of cross-section, in.________
Edge which cracked______________
Diameter of pin, in.______________
Ratio of pin diameter to
thickness of specimen____________

Compression Test

With the sample of structural grade steel, there will be furnished two compression specimens of such a size that they conform to A.S.T.M. Designation E9-33T, or later, for size of compression test specimens (of medium length). Obtain the length, diameter, and Rockwell hardness of each specimen before testing. Place one specimen in the compression tool, being careful that the crosshead slides easily on the guide posts and that the specimen is centered on the lower seat. The essential features of a compression tool are shown in Figures 42 and 45. Load should be applied to the spherical bearing through the flat head of the testing machine at slow speed until the yield point is reached. The drop of beam may not last long, due to the short length of specimen as compared to the tension test and, therefore, the operator should be cautious to keep the beam carefully balanced up to the yield. Note the yield point both by drop of beam and scaling.

Continue to apply load to the specimen at a higher rate of speed until a total load of 50,000 lb. has been applied, or until the specimen is about one half its original length. It should be noted that the ductile steel does not rupture in compression, but merely deforms plastically. Determine the Rockwell hardness after the specimen has been removed from the compression tool.

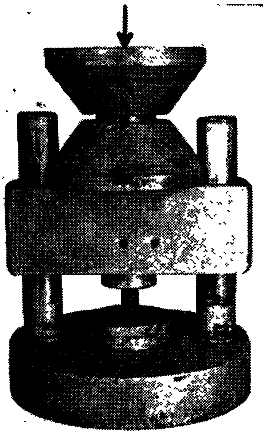


FIG. 45. Compression tool set up for test with specimen in place. Load applied to spherical bearing block as shown.

Repeat this procedure for the other compression specimen but do not apply load beyond the yield point. Again obtain the final hardness and compare it with that of the cold-worked specimen.

Cold-Bend Test

The cold-bend test is usually considered as providing a qualitative measure of a material's ability to be formed during a metal working operation. In its simplest form it consists merely of bending a sample of the material flat upon itself and noting if any cracks have occurred. Should the material crack it may be necessary to bend a similar specimen around various sizes of pins in order to determine the minimum radius of bend. A specification for such bending properties may be found in A.S.T.M. Designation A7-39, or later.

Obtain the dimensions of the specimen and note the condition of the edges as smooth or rough. Place the pre-bent sample between two steel plates and in the testing machine as shown in Figure 46(a). Apply sufficient load, using the testing machine merely as a press, to bend the specimen flat upon itself. Remove the load and examine the severely bent portion of the specimen for any cracks. A characteristic failure is shown in Figure 46(b). Other types of cold-bend specimens are shown in Figure 47.

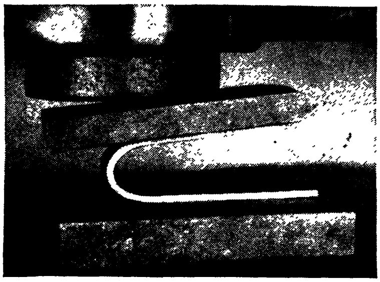


FIG. 46(a). Cold-bend specimen in testing machine before application of load.

FIG. 46(b). Characteristic failure (*right*) of steel plate when bent cold. Sound specimen at left.

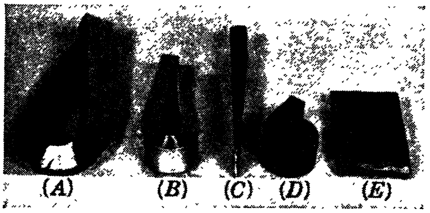


FIG. 47. Various types of cold-bend test specimens: (a) Side-bend test of welded steel; failure at edge of weld. (b) Stainless steel bent around a pin without failure. (c) Ductility test specimen of malleable iron. (d) Specimen of (c) after absorbing 40 impact blows of 70 ft.-lb. each. (e) 0.19 per cent carbon plate bent flat. Note failure at rough sheared edges.

PREPARATION OF REPORT

DISCUSSION

1. In the table below compare the tensile properties of the wrought iron with standard A.S.T.M. specifications for the material. Include also the low carbon steel specimen tested in Experiment 3.

	Tensile strength, psi.	Yield point, psi.	Elongation in 8 in., per cent	Is specimen accepted?
Test results				
A.S.T.M. Spec.*				
Pass or fail?				
Low carbon steel, Exp. 3				

*A.S.T.M Designation______________

2. Compare the yield point stresses in tension and compression.
3. What property determines the ability of a material to be used as a short column (compression member)? Why?
   What property determines the ability of a material to be used as a long column? Why?
4. The ratio of shearing strength to the tensile strength is usually about 0.8 for low and medium carbon steel and 0.6 for high carbon steel. How do these averages compare with the values obtained in this test?
5. Compare the results of the cold-bend test with the requirements for Steel for Bridges and Buildings (A.S.T.M. Designation A7-39, or later). Would the material be accepted or rejected?

EXPERIMENT 5

FLEXURAL TEST OF A WOOD BEAM

The flexure test is one of the few experimental procedures in which all three forms of stress, tension, compression, and shear, are found in one specimen and as a result of a single applied load. For this reason, a beam may be expected to fail as a result of overloading in any of these three ways. When the material is ductile and the failure is in compression, the beam will merely bend plastically and will not rupture. If the material is brittle in the lower fibers, however, and failure occurs in compression, the beam will subsequently be overloaded in tension, and will actually fail by rupture. It is desirable, therefore, that the student should understand the mechanics of beams in flexure and realize the part that physical properties as well as dimensions have in determining the type of failure.

In Figure 48 are shown simple beams (ends free to rotate and resting on only two supports) subjected to three forms of loading. Immediately below each of these sketches are the shear diagrams for the condition of loading imposed on the beam. This shear diagram is the summation of the vertical forces on either side of the section of the beam being studied. Below these shear diagrams are the corresponding bending moment diagrams. These latter figures indicate pictorially the summation of every applied force on either side of the section times the distance of that force from the section (or the moment of the applied force about the section). Shear and moment diagrams are helpful in visualizing the forces which a beam must resist. When an imaginary section is passed through the beam in Figure 48(a), the forces on the section and the beam are as shown in Figure 49. As the beam bends, the upper fibers are shortened and must, therefore, be in compression, whereas the lower fibers are lengthened and are therefore in tension. The plane of transition from compressive stresses to tensile stresses represents a layer of fibers which are subjected to zero stress and consequently do not elongate or shorten when the beam is loaded. This plane is termed the neutral axis and in a rectangular or symmetrical beam is located at the mid-depth. For unsymmetrical sections the neutral axis coincides with the centroidal axis as it also does for symmetrical sections. The stress on any fiber in the beam varies directly as the distance of that fiber from the neutral axis and may be found from the relationship

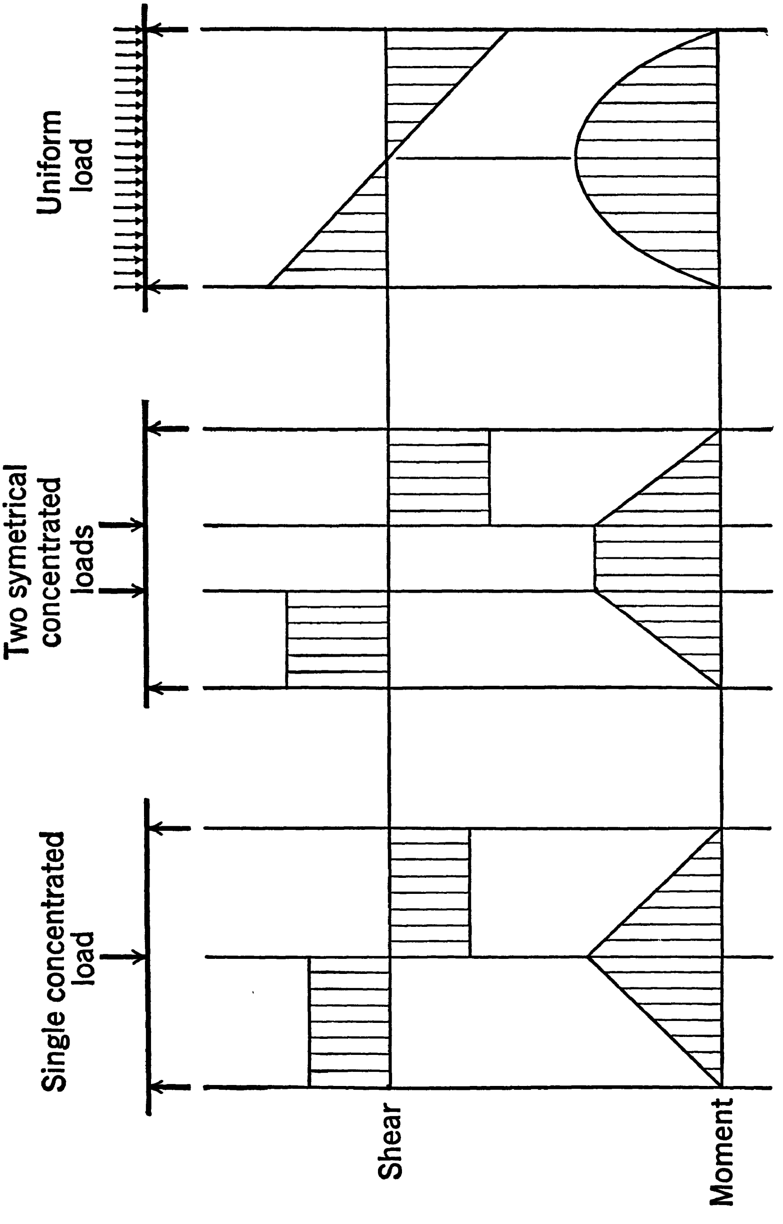


FIG. 48. Shear and moment diagrams for various conditions of loading.

$$s = \frac{Mc}{I}$$

in which s = stress on fiber at a distance, c, from the neutral axis, psi. (tension or compression).

M = bending moment at section studied, in.-lb.

I = moment of inertia of the cross section with respect to the neutral axis. The value of I depends on the shape, width, and depth of the section. For a rectangular beam it is equal to $bd^3/12$, where b is the breadth of the beam and d the depth. For a round beam of diameter, d, the value of I is $\pi d^4/64$. The value of the moment of inertia is expressed in in.^{4} For structural sections it may be found in structural steel or aluminum handbooks.

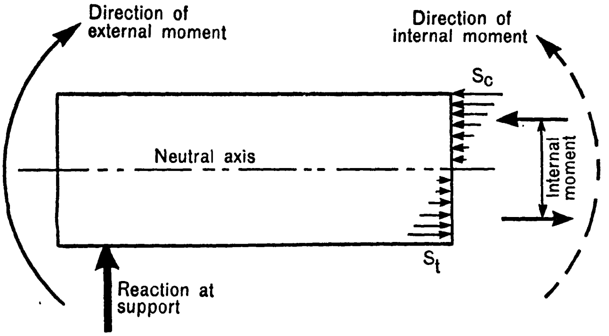


FIG. 49. External and internal forces on a beam shown by cutting the beam. Failure occurs when the internal moment no longer equals the external moment.

For the derivation of this formula see any strength of materials text.

The summation of the stresses across the section produces an internal resisting moment which is equal in magnitude but opposite in sign to the acting external moment. This condition exists so long as the beam is supporting the load. When the external moment exceeds the internal moment, rupture occurs.

The vertical shearing forces are often of importance in structural design as may be seen from a study of $s = Mc/I$. For any bending moment it is a simple matter to increase the depth of section, thus increasing the value for I and, consequently, lowering the value of s. To guard against failure by vertical shear, V, the entire cross-sectional area, A, must be such that the permissible shearing stress is not exceeded or so that $s_s = V/A$. Of more importance than vertical shear, particularly in the design of wood, concrete, and composite beams (built up layer by layer), is the horizontal shear caused by the bending action. In Figure 50(a) is shown a small cube cut from near the top or bottom fibers of a beam and with the vertical shearing forces indicated. As shown the block would not be in equilibrium and it can be seen that additional horizontal shearing forces, as shown in Figure 50(b), must act on the cube. To produce equilibrium, the couples thus formed must be equal in magnitude but opposite in sign. It may be concluded, therefore, that the horizontal and vertical shearing stresses at any point in the beam are equal. Further, it may be shown from strength of materials that the value of the shearing stress is

$$s_s = \frac{V}{Ib}(A'\bar{y})$$

in which s_s = average shearing stress on a section of area A', psi.
I and b the same as before.
$\bar{y}$ = the statical moment of the area A' about the neutral axis, in.^{3}

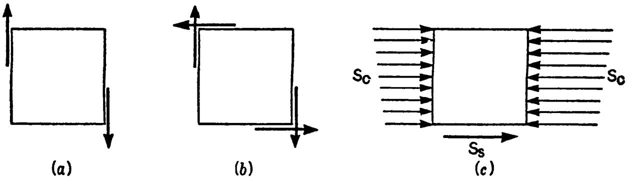


FIG. 50. Shearing and direct stresses on an element taken from the beam in Figure 49.

For a beam of rectangular cross section, Figure 50(c), the horizontal or vertical shearing stress at the neutral axis would be

$$s_s = \frac{V}{bd^3/12\,(b)}\left(\frac{bd}{2}\right)\left(\frac{d}{4}\right) = \frac{3V}{2bd} = 1.5\frac{V}{A}$$

or the maximum shearing stress is 50 per cent greater than the average shearing stress over the entire section. Further, it may be seen that s_s is a maximum at that point along the beam where V is a maximum. This point may be determined from the shear diagram. Finally, since $\bar{y}$ is a maximum when taken about the neutral axis, the greatest value for shearing stress across the section will be found along that plane (neutral axis). The complete picture of the distribution of shearing stresses in the beam is shown in Figure 51.

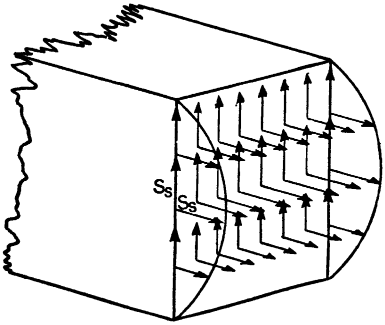


FIG. 51. Distribution of vertical and horizontal shearing stresses over cross section of beam. Vertical shear equals the horizontal shear at any one point.

When the stresses in the outer fiber of a beam exceed the proportional elastic limit the remaining fibers must assume more stress and at a faster rate than before. The distribution of stress over the cross section is then something other than a straight line relationship, appearing as shown in Figure 52. When the shape of the cross section is not symmetrical about the neutral axis, or when the material's moduli of elasticity in tension and compression are not the same,* the neutral axis shifts when the beam is stressed beyond the proportional elastic limit. In this case, also, the stresses are not distributed in a straight line relationship across the section. When the maximum value for M is substituted in the flexure formula the result obtained for s is therefore not correct. It is of value for comparative purposes, however, when the stress thus obtained is termed the modulus of rupture. Thus

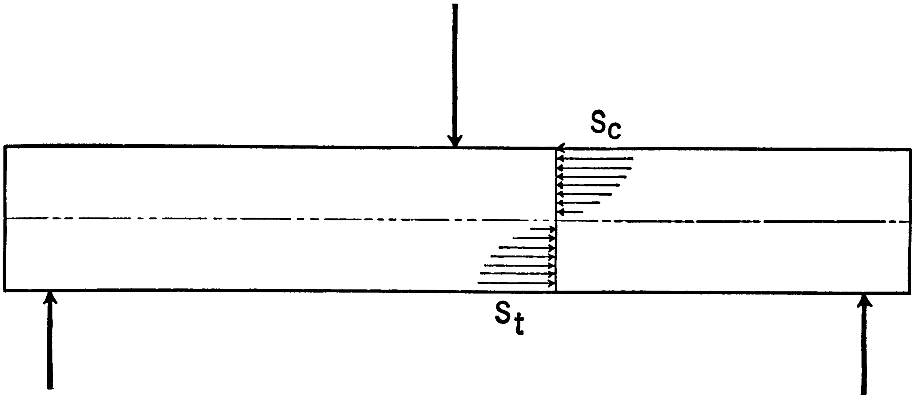


FIG. 52. Distribution of stress in beam when stresses in outer fibers exceed proportional elastic limit. Note that the stresses do not vary directly as their distance from the neutral axis.

$$s_r = \frac{M_{\text{max.}}c}{I}$$

in which s_r = modulus of rupture, psi. The fictious stress that exists at the maximum bending moment.

M, c, and I the same as before.

The modulus of rupture is not the ultimate strength of the material nor can a value for ultimate strength be substituted in this relationship in an effort to forecast the maximum load which a beam will support. It may be used for comparative purposes for different materials when the beams tested are symmetrical or alike in shape of cross section. The modulus of rupture is of value in evaluating the results of tests of brittle materials.

The deflection of a beam varies directly as the load and span, and inversely as the moment of inertia of the cross section and the modulus of elasticity of the material. For various conditions of loading the center-line deflection may be calculated from the following:

---

* Actually no material could fulfill this requirement although most metals do so within reasonable limits. Non-homogeneous materials such as wood obviously cannot meet this condition.

1. Concentrated load at center of span, L, Figure 48(a).

$$\Delta = \frac{PL^3}{48EI}$$

2. Two equal symmetrically placed concentrated loads, each a distance x from the support, Figure 48(b).

$$\Delta = \frac{Px}{24EI}(3L^2 - 4x^2)$$

3. Uniform load, w lb. per ft., over entire span, Figure 48(c).

$$\Delta = \frac{5wL^4}{384EI}$$

Since wood is weak in shear parallel to the grain, a wood beam may fail by horizontal shear under proper conditions. Ordinarily wood fails first in compression under beam action so that the lower fibers must be stressed higher and higher in tension and eventually fail as is shown in Figure 53.

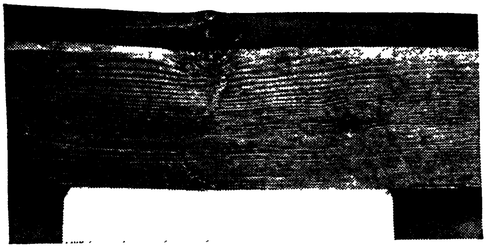


FIG. 53. Initial failure of wood beam in compression (*top*) leading to final failure in tension (*below*). Compression failure aided by knot.

Certain defects are found in wood which may aid failure in bending. They are briefly as follows:

Knots—Caused by limbs growing out from the main trunk of the tree. They are classified as loose and tight. Only a tight knot will withstand compression. Neither kind will withstand tension.

Shakes—A shrinkage crack along the grain due to drying the wood improperly prior to use.

Checks—A shrinkage crack across the grain due to improper drying.

Inclined grain—Improper cutting or growth will yield a beam in which the fibers are not parallel to the bottom or top of the section. Reduces strength considerably.

That these defects aid failure is apparent from Figure 54.

The properties of the wood itself are dependent upon its density. The density in turn is dependent upon the relative amounts of spring and summer wood. During the spring months the tree grows rapidly, yielding a low density wood, while during the summer it grows slowly, producing a higher density and thus stronger wood. The annular ring thus consists of two distinct portions, light spring wood and darker summer wood. It is desirable to have as large a proportion of summer wood as possible.

The brief analysis made of beam action here may be amplified by studying any strength of materials text. The individual importance and considerations of tension, compression, and shear should be visualized by the student in this test, as well as the manner of satisfactorily making beam tests.

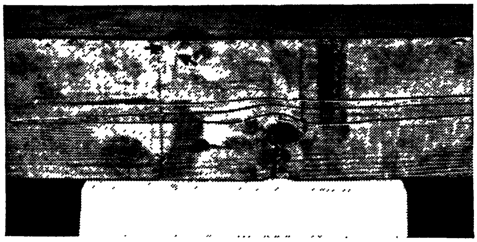


FIG. 54. Failure of wood beam aided by knot and check. The knot aided final failure in tension, while the check produced the partial horizontal shear failure shown. Initial compression failure indicated by arrows.

EXPERIMENTAL PROCEDURE

APPARATUS—A universal testing machine, a rigid supporting beam or beams, rocker end bearings, bearing plates, bearing block, steel roller, deflectometer or similar equipment, scale, and calipers.

MATERIAL—A commercial grade of structural wood cut to a properly proportioned beam size. For any type of beam the span should be equal to or greater than a constant, K, times the ratio of the modulus of rupture to the maximum shearing stress. Various constants are

1. For a rectangular beam loaded at the mid-span, $K = 0.5d$, where $d =$ depth, in.
2. For a rectangular beam symmetrically loaded with two equal loads, each a distance x from the supports, $K = 0.25\ d/x$.
3. For a beam of circular cross section and loaded as in 2, $K = 0.167\ d/x$.

These proportions will generally produce failure in a sound beam by tension or compression rather than by horizontal shear.

Carefully examine the beam, noting the kind of wood, its physical characteristics, and any defects that may be present. Obtain the dimensions of the beam, its weight, the approximate number of annular rings per inch, and the percentage of summer wood to total annular ring. The moisture content of the wood will not be determined in this test, since it usually reaches a constant value when timber is stored before using.

The beam should be placed on end supports that will permit both longitudinal and transverse rocking when the specimen bends under load. Such a support is shown in Figure 55. Load should be applied through a bearing block and the specimen should rest on bearing plates at the support. Deflections may be obtained with a Wissler dial as shown in Figure 55, or with a dial gage as shown in Figure 56. In taking deflection measurements it is important to remember that all readings must be referred to the supports on which the beam rests and not to some other reference point which is independent of any settlement of supports which might occur. The steel supporting beams tend to bend upward in the middle when taking the beam reaction at the ends. This deflection may be slight but when added to the actual downward deflection of the beam it tends to give an exaggerated total deflection.

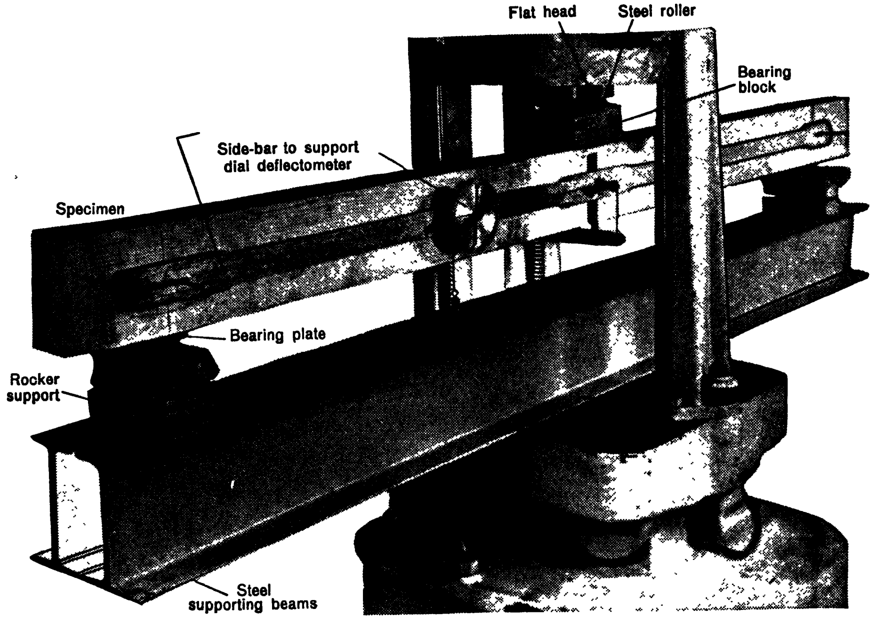


FIG. 55. Timber beam in position ready for test. In this case deflection is obtained with a Wissler dial, but a dial gage may be used as shown in Figure 56. Note that deflections are referred to supports on which beam rests.

Balance the weighing beam to zero with the specimen, supporting beams, and other apparatus in place on the weighing table. The loads indicated by the weighing system of the testing machine will then be the correct readings and no load corrections will be necessary. Apply a small initial load and obtain the initial dial reading for each deflection station. Apply load continuously throughout the test and read the dials at the increments of load indicated by the instructor. When the increment between dial readings increases, the beam has passed its limit of elastic

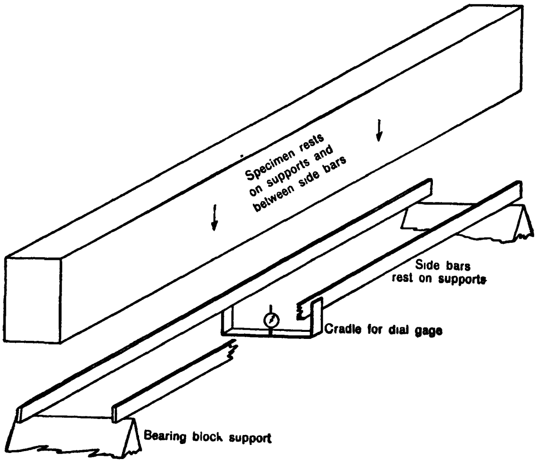

Specimen rests on supports and between side bars
Side bars rest on supports
Cradle for dial gage
Bearing block support

FIG. 56. Deflectometer for obtaining deflections of a beam independent of support settlement. Dial gages may also be attached at additional points, such as quarter or third points.

action. Watch for the initial compression failure in the upper fibers. When the first crack occurs, or when the deflection of the beam becomes excessive, remove the deflection apparatus and then apply load to failure, recording the maximum load. Study the manner of failure and indicate any opinion on the data sheet.

EXPERIMENT 5

STATIC BENDING TEST OF A TIMBER BEAM

Name ________________________________ Date ________________

Load, lb.	Deflection, inches			Deflection, Corrected to Zero		
	At center line	At third point	At quarter point	At center line	At third point	At quarter point

Material ________________________

Width of specimen, in. ________________________

Depth of specimen, in. ________________________

Overall length, in. ________________________

Weight, lb. ________________________

Distance between supports (span), in. ____________

Approximate number of annular rings per inch ________________________

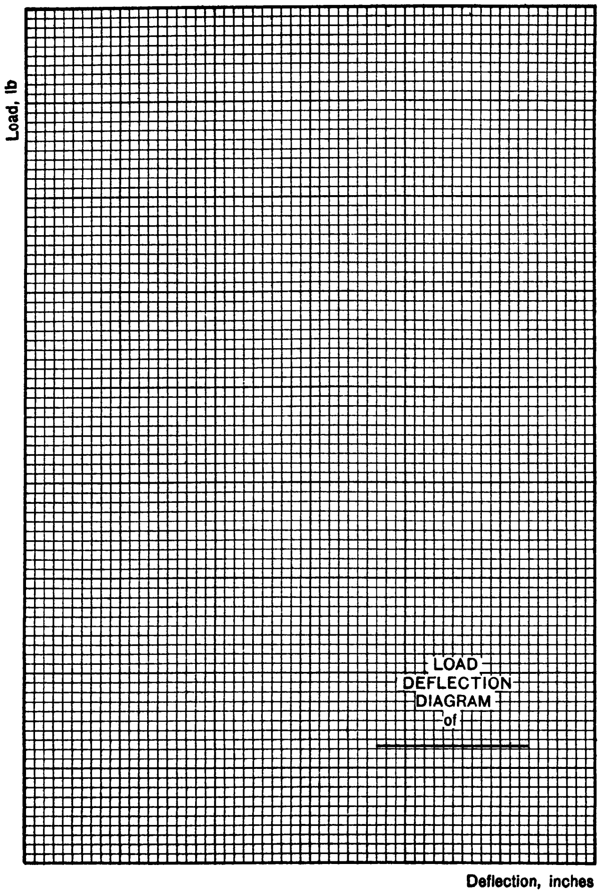
Approximate percentage of summer wood ________________________

Sample data sheet for Experiment 5.

PREPARATION OF REPORT

LOAD-DEFLECTION DIAGRAM

After the deflection data has been corrected to zero, plot the load-deflection diagram on cross-section paper similar to the sample curve sheet shown. Select units for the coordinate scales so that the entire sheet of graph paper is utilized. When deflections are measured at stations other than the center line, plot all curves on the same sheet and indicate the position on the corresponding curve.



Sample sheet of cross-section paper for load-deflection diagram of wood in Experiment 5. Coordinate scales to be filled in.

COMPUTATIONS

From the data or curve sheet compute the following, giving examples for each and stating units for the answers:

1. Stress at proportional elastic limit. Obtain load at this point from the load-deflection diagram and, substituting in the flexure formula, calculate the unit stress at the proportional elastic limit.

2. Modulus of rupture.
3. Modulus of elasticity in bending. Select a load and corresponding deflection on the straight-line portion of the load-deflection diagram. Substitute in the relationship for deflection for the type of loading used and solve for E.
4. Modulus of elastic resilience from load-deflection diagram. (In total in.-lb. for the entire specimen.)
5. Maximum horizontal shearing stress.
6. Unit weight.

DISCUSSION

1. In the following table compare the properties indicated with average values posted on the bulletin board:

	Unit weight lb. per cu. ft.	Modulus of rupture, psi.	Modulus of elasticity, psi.	Horizontal shear, psi.
Test value				
Average value				

2. Why is it necessary that the ends of the beam be permitted to rotate longitudinally or transversely?
3. What effect does the modulus of elasticity have upon the deflection of a beam?
4. A beam makes a good spring because of its bending action and because the proper value of modulus of elasticity can be used. In the following table are given some average values of E for various materials. Calculate the deflection of each of these materials for the same size of specimen and load at the proportional elastic limit as for the wood beam tested.

Material	Modulus of elasticity, psi.	Deflection at proportional elastic limit, in.	Ratio of deflection of this material to deflection of wood
Wood tested			
Steel	30,000,000		
Aluminum	10,000,000		
Cast iron	12,000,000		

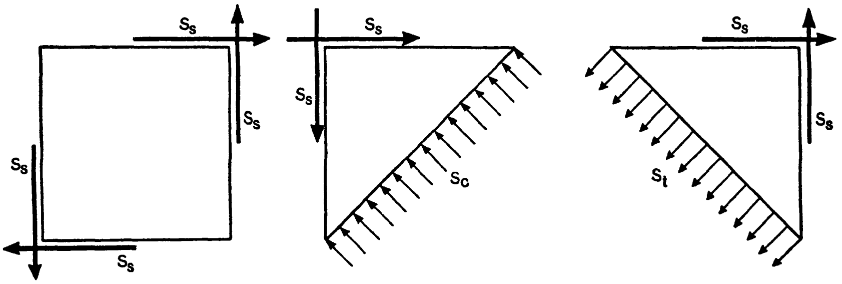
From this table which material would make the best spring to absorb energy loads elastically within the loading range applied to the wood? Why?

5. As a result of this test, is wood stronger in tension or compression? Why?

EXPERIMENT 6

TORSION TESTS OF DUCTILE AND BRITTLE MATERIALS

Line shafting, motor drive shafts, and airplane propellers are good examples of mechanical parts subjected to twisting loads. Under such a loading condition shearing stresses are set up in the member and the stresses on a unit cube of material are as shown in Figure 57(a). When the sections of Figures 57(b) or 57(c) are passed diagonally through the cube, however, it is seen that the shearing stresses are resisted internally by tensile or compressive stress, depending upon the direction of the shearing stress. By summing forces in the direction perpendicular to the diagonal plane and obtaining the relationship between shearing stresses and tensile or compressive stresses it is found that they are equal ($s_t = s_s$ and $s_c = s_s$). In Figure 58 is shown a shaft with the torque applied and the surface stresses as indicated. This figure illustrates that the torsion test, like the beam test, subjects a specimen to all three forms of stress simultaneously. The manner of failure will then be governed by the lowest stress. Ductile materials which are weaker in shear than in tension or compression will therefore fail in shear, whereas brittle materials, which are weaker in tension than in compression or shear, will fail in tension, as shown in Figure 59. As in beams, the longitudinal shearing stress in a twisted shaft is equal to the transverse shearing stress.



(a) (b) (c)

FIG. 57. Applied shearing stresses set up internal tensile and compressive stresses.

The distribution of stresses in a shaft subjected to twisting is shown

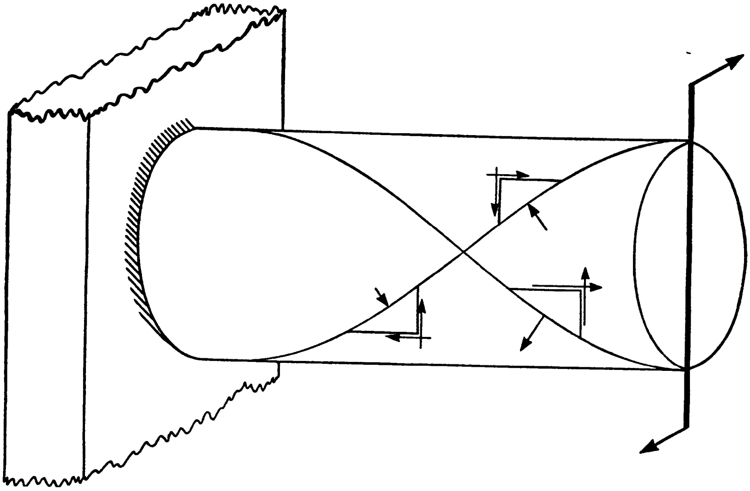


FIG. 58. Surface stresses in twisted shaft are combinations of shear and tension, or shear and compression.

in Figure 60(a). Notice the similarity to the stress distribution in a beam, the longitudinal axis of the shaft being equivalent to the neutral axis of the beam. The shearing stresses in a shaft may be determined from the relationship

$$s_s = \frac{Tc}{J}$$

in which s_s = shearing stress on a fiber at a distance c from the longitudinal axis, psi.

T = applied torque, in.-lb.

J = polar moment of inertia of the cross section (the moment of inertia about a piercing diameter). For a circular section of diameter, d, $J = \pi d^4/32$ in.^{4}

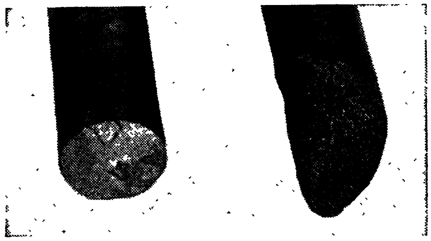


FIG. 59. Failure of materials in torsion. Ductile steel (*left*) fails in shear and brittle cast iron (*right*) fails in tension. Shear break is at 90 degrees to longitudinal axis and tension break at 45 degrees, as shown in Figures 57 and 58.

When the maximum value of T is used in this relationship, the result obtained is the "apparent" ultimate shearing strength.

When torque is applied to a shaft, the deformation resulting from this torsional load is called *twist*. It, like the deformation in a beam, varies directly as the load and length (same as span for a beam), and inversely as the shearing modulus of elasticity (modulus of rigidity) and the polar moment of inertia. The twist may be determined from the relationship

$$\theta = \frac{TL}{GJ}$$

in which θ = angular twist of shaft, radians (one radian = 57.3 degrees).
L = length over which θ is measured, in.
G = modulus of rigidity or modulus of elasticity in shear, psi.
J same as before.

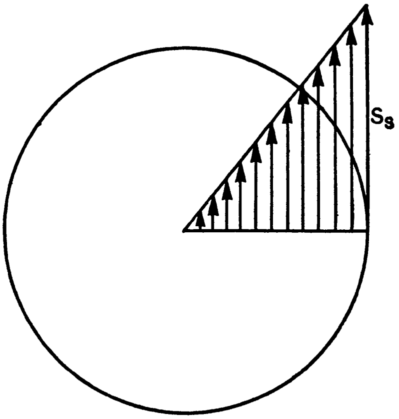


FIG. 60(a). Distribution of shearing stresses in shaft subjected to twisting.

Referring again to Equation (9) it may be seen that G can be calculated from E and Poisson's ratio or, if E and G are determined experimentally, Poisson's ratio may be calculated.

The importance of the torsion test lies in the fact that it represents three tests in one. A study of the torsional failure of a material will tell whether it is weakest in tension, compression, or shear. Because of the expense and time required to make torsion tests they are not specified as standard. Some organizations use the test to indicate ductility by counting the total number of times a material can be twisted before fracturing. In this experiment the student should form a clear understanding of the fundamental concepts presented in Figure 57 and how they may be used in forecasting failures (or preventing them in design). If the torsion test is compared closely with the more familiar flexure test this understanding may become clearer.

EXPERIMENTAL PROCEDURE

APPARATUS—A torsion testing machine of sufficient capacity to fracture the specimens used, a torsional strainometer, micrometer, divider, and scale.

MATERIAL—Samples of ductile and brittle materials, such as mild steel and cast iron, aluminum and plastics, copper and glass, etc.

A torsion testing machine consists essentially of two jaws or chucks for holding a specimen to be subjected to twisting. One jaw is attached to a power source to apply torque and the other is fitted with a pendulum with which to measure the torque. If a specimen is rigid it will transmit the applied torque (minus elastic or plastic twist) to the pendulum, raising the pendulum and thus balancing the torque. Supplementary apparatus permits the observation of the total number of complete turns which the specimen makes, the twist (less than 360°) of the power end of the specimen and of the pendulum end of the specimen, the applied torque, and the lengthening or shortening of the specimen. Although these may not all be available on all machines they are readily obtainable. A torsion machine on which these features are indicated is shown in Figure 60(b). Other torsion testing machines are shown in Figures 61 and 62.

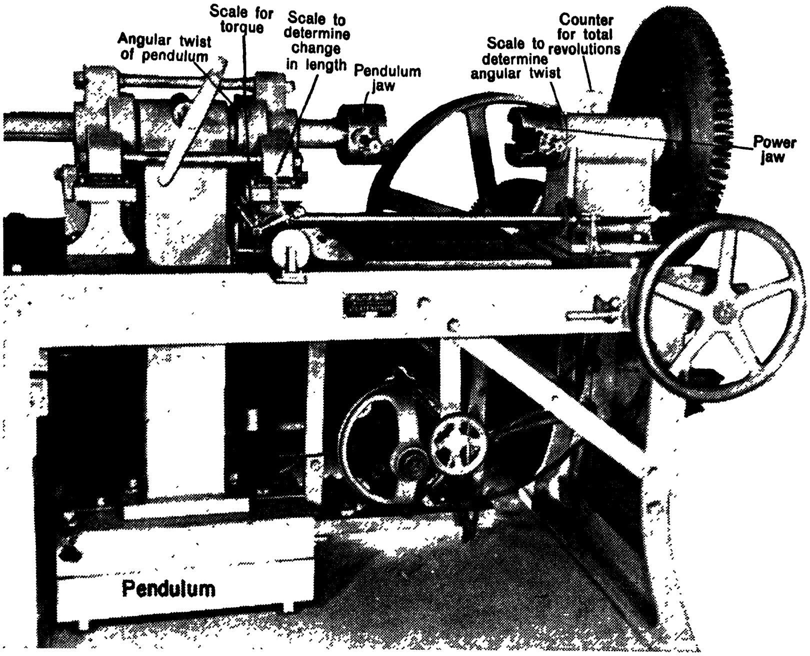

Angular twist of pendulum
Scale for torque
Scale to determine change in length
Pendulum jaw
Scale to determine angular twist
Counter for total revolutions
Power jaw
Pendulum

Fig. 60(b). Torsion testing machine (Amsler-Laffon) of 12,000 in.-lb. capacity. Essential features are as shown.

The scales which measure the net twist of the specimen are not satisfactory for determining the small twists observed during elastic action. To obtain this small angular elastic deformation it is necessary to use a *torsional strainometer,* also referred to as a *troptometer.* This device is similar in operation to an extensometer except that it measures angular

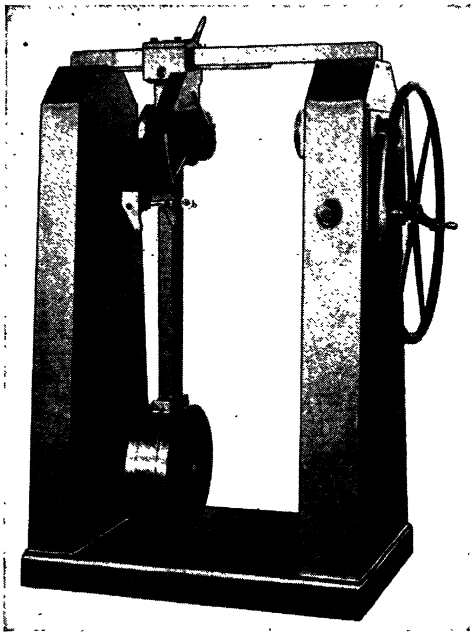


FIG. 61. 10,000 in.-lb. capacity Riehle torsion machine. (Courtesy American Machine and Metals, Inc., Riehle Testing Machine Division)

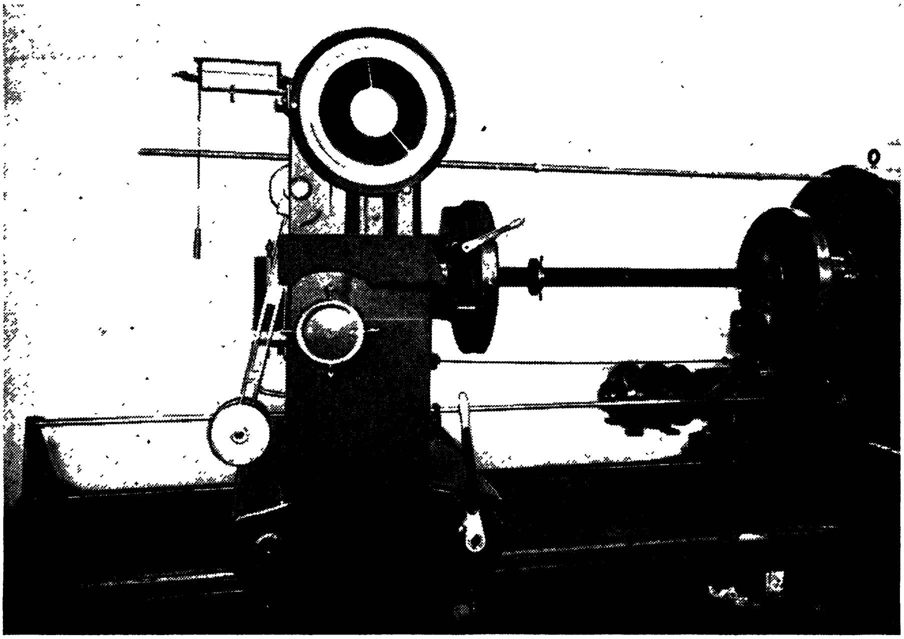


FIG. 62. 300,000 in.-lb. capacity Riehle torsion machine with self-indicating dial and autographic recorder. (Courtesy American Machine and Metals, Inc., Riehle Testing Machine Division)

strain. As shown in Figure 63, the torsional strainometer consists of two separate collars mounted over a gage length L. One collar, A, is considered a fixed reference point and the other collar twists with respect to it. The change, angle θ, between the arms attached to the collars, is the angular twist. This angle is measured as shown in Figure 64. Any device which will measure linear dimensions to 0.001 in. may be used to determine the change in chord length AB. Since for small angles the chord AB equals the arc AB, the angle θ, in radians, may be found from

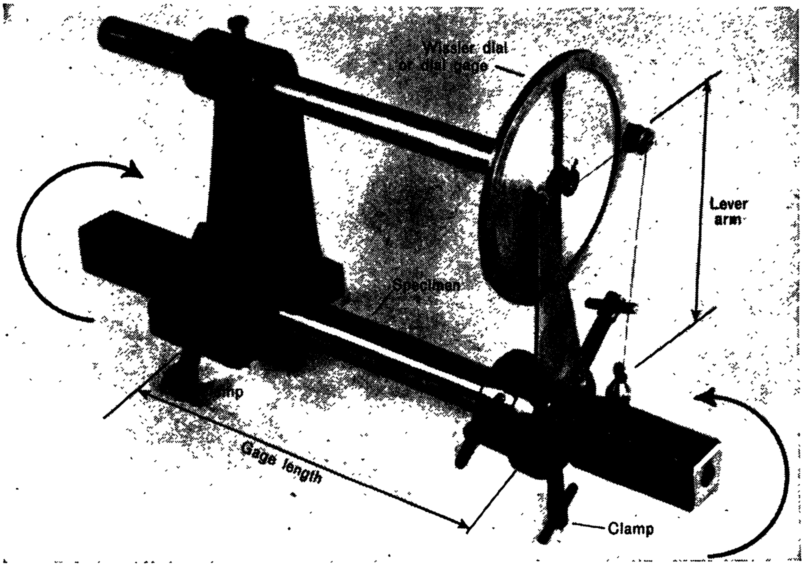


FIG. 63. Essential parts of a torsional strainometer.

$$\theta = \frac{AB}{a}$$

in which a = lever arm of the torsional strainometer, in.

The chord length AB is the reading obtained from the indicating dial of the meter.

Before placing a specimen in the torsion testing machine, operate the chuck at the power end, also the pendulum, and note the manner in which the various scales provide pertinent data. With the torsional strainometer securely attached, place the steel specimen in the machine, centering it carefully and solidly in the grips. Obtain the dimensions of the specimen, the zero readings of all scales, and the zero reading of the torsional strainometer. Apply torque in the increments given by the instructor, recording the torsional strainometer reading for each load until the proportional elastic limit is reached. Reduce the increment of torque and continue to apply load until severe plastic deformation is obtained. When certain that the material is well within its plastic range, reduce the torque to zero in at least four increments and determine the twist at each reduced torque. Increase the torque to its former value, again noting the twist for at least four increments of torque. Remove the torsional strainometer

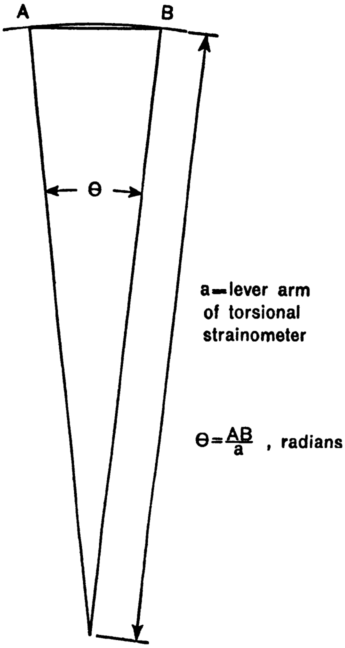


Fig. 64. Method of determining twist (in radians) from torsional strainometer.

EXPERIMENT 6

TORSION TEST OF METALS

Name__________________________________ Date________________

Torque, ft.-lb.	Torque, in.-lb.	Torsion Meter Readings			
		As read	Corrected to zero	Radians	Radians per inch of gage length

Material________________________ Lever arm of torsion meter, in.________

Original diameter, in.____________________ Gage length of torsion meter, in.________

Length between shoulders, in.______________

Sample data sheet Number 1 for Experiment 6.

and twist the specimen to fracture, recording necessary information on the data sheet and noting the form of fracture.

EXPERIMENT 6

TORSION TEST OF METALS

Name________________________________ Date____________________

DUCTILE MATERIAL

Material____________________________________
Diameter, in.________________________________
Length between shoulders, in.____________________
Readings:

Scale	Units	Initial reading	Yield reading	Ultimate reading
Total revolutions of twist				
Twist of power end of specimen				
Twist of pendulum end of specimen				
Torque				
Change of length				

Type of fracture____________________

BRITTLE MATERIAL

Material____________________________________
Diameter, in. ________________________________
Length between shoulders, in.____________________
Readings:

Scale	Units	Initial reading	Ultimate reading
Total revolutions of twist			
Twist of power end of specimen			
Twist of pendulum end of specimen			
Torque			
Change of length			

Type of fracture____________________

Sample data sheet Number 2 for Experiment 6.

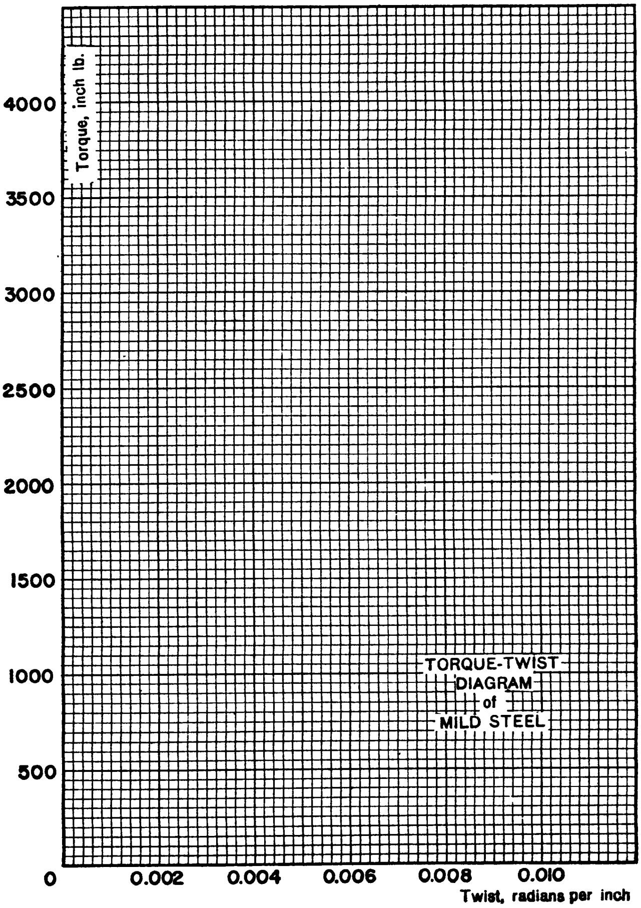
If the torsion testing machine has an autographic attachment for automatically recording the torque twist diagram, obtain a copy of this diagram by tracing over the original.

This procedure may be repeated for the brittle material or the brittle specimen may merely be tested to failure and all necessary data obtained from appropriate scales.

Preparation of Report

TORQUE TWIST DIAGRAM

Convert the data to unit values following the guide given by the column headings on the sample data sheet and plot the torque twist diagram. The cross-section paper should follow the form of the sample curve sheet shown. The cycle of unloading and reloading should also be plotted. If the coordinate scales are not ample enough to show this cycle on the graph paper, plot an additional diagram to a supplementary scale for twist and note this scale along the abscissae.



Sample sheet of cross-section paper for torque-twist diagram in Experiment 6, showing coordinate scales.

COMPUTATIONS

From the data or torque twist diagram compute the following, giving numerical examples and stating the units for each result:

1. Shearing stress at proportional elastic limit from torque twist diagram using $s_s = Tc/J$.

2. Shearing stress at yield point.
3. Apparent ultimate shearing stress for both ductile and brittle materials.
4. The angle of twist per inch of gage length at fracture for both ductile and brittle materials.
5. The modulus of rigidity (modulus of elasticity in shear) from $\theta = TL/GJ$. (Select a point on the straight line portion of the diagram.)
6. Using the relationship of Equation (9) calculate the value of Poisson's ratio for ....

DISCUSSION

1. The loop formed on the torque twist diagram by the cycle of loading and unloading is termed a *hysteresis* loop and represents energy lost during such a cycle. In what way is the energy lost? Is the hysteresis loop of most importance in steel or rubber? Why?
2. In Figure 65 are shown the fractured ends of two different steels tested in tension. The specimen which reduced in cross-sectional area was an ordinary mild steel having the properties indicated. The other specimen was twisted far out in its plastic range in torsion and then tested in tension with the results shown. Account for the difference in strength and ductility.

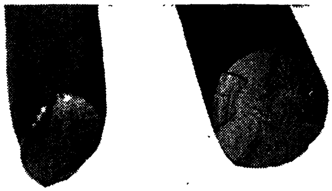


Fig. 65. Effect of cold working in torsion upon the physical properties of 0.15 per cent carbon steel in tension. Original material after tension test at left. Twisted material after tension test at right. Original properties: ultimate strength = 53,000 psi.; stress at yield point = 33,700 psi.; elongation in 2 in. = 56 per cent; reduction in area = 65 per cent. Final properties: ultimate strength = 96,800 psi.; no yield point; elongation in 2 in. = 5 per cent; reduction in area = 0 per cent.

3. By which method can the shear properties of a material be best evaluated: the cross-shearing test used in Experiment 4 or the torsion test? Why?
4. Why is the shearing stress obtained in computation 3 termed the "apparent" ultimate shearing stress? In order to obtain a more exact value for ultimate shearing strength, what form of cross section should be used for the test specimen? Why?

EXPERIMENT 7

IMPACT TESTS OF DUCTILE AND BRITTLE MATERIALS

The tests made thus far have involved slowly applied loads. These static loads, as they are called, are not the only types of loading to which a material may be subjected. As has been pointed out previously, loads may be applied statically (slowly), dynamically (sudden energy loads), or by repetition. The properties of various materials under the second type of loading will be shown in this experiment. It has been shown that the entire area under the stress-strain diagram is a measure of fracture toughess, a valuable tool in forecasting the ability of a material to resist suddenly applied energy loads (impact). The impact test is a qualitative type of test designed to evaluate this property of fracture toughness with a minimum of difficulty.

Impact test loads may be applied in many ways. In one type the weight is allowed to fall onto the specimen from progressively greater heights until failure occurs. Railroad rails and framed structural members are occasionally tested in this manner. For laboratory and general acceptance tests the Charpy or Izod impact test is used. Either of the two tests employs a beam type specimen which has a carefully machined standard notch cut into it to act as a stress raiser and thus induce failure, particularly of ductile materials. Standard specimens of this type are shown in Figure 66. As indicated there, the dimensions and method of test must conform to A.S.T.M. Designation E23-41T, or later. The Charpy test employs the simple beam, of span, size, etc. shown in Figure 66, supported at the ends and suddenly loaded at the mid-span and on the face away from the notch. The Izod test makes use of the cantilever beam loaded with reference to the clamped end of the specimen as shown in Figure 66.

The important parts of an impact testing machine are shown in Figure 67. As the pendulum is raised to an initial starting position it is given potential energy. When the pendulum is released it swings downward and imparts this energy to the specimen, neglecting loss due to friction. The specimen thus absorbs a portion of the potential energy, and the angle through which the pendulum rises after striking the specimen is a measure of this absorbed energy.

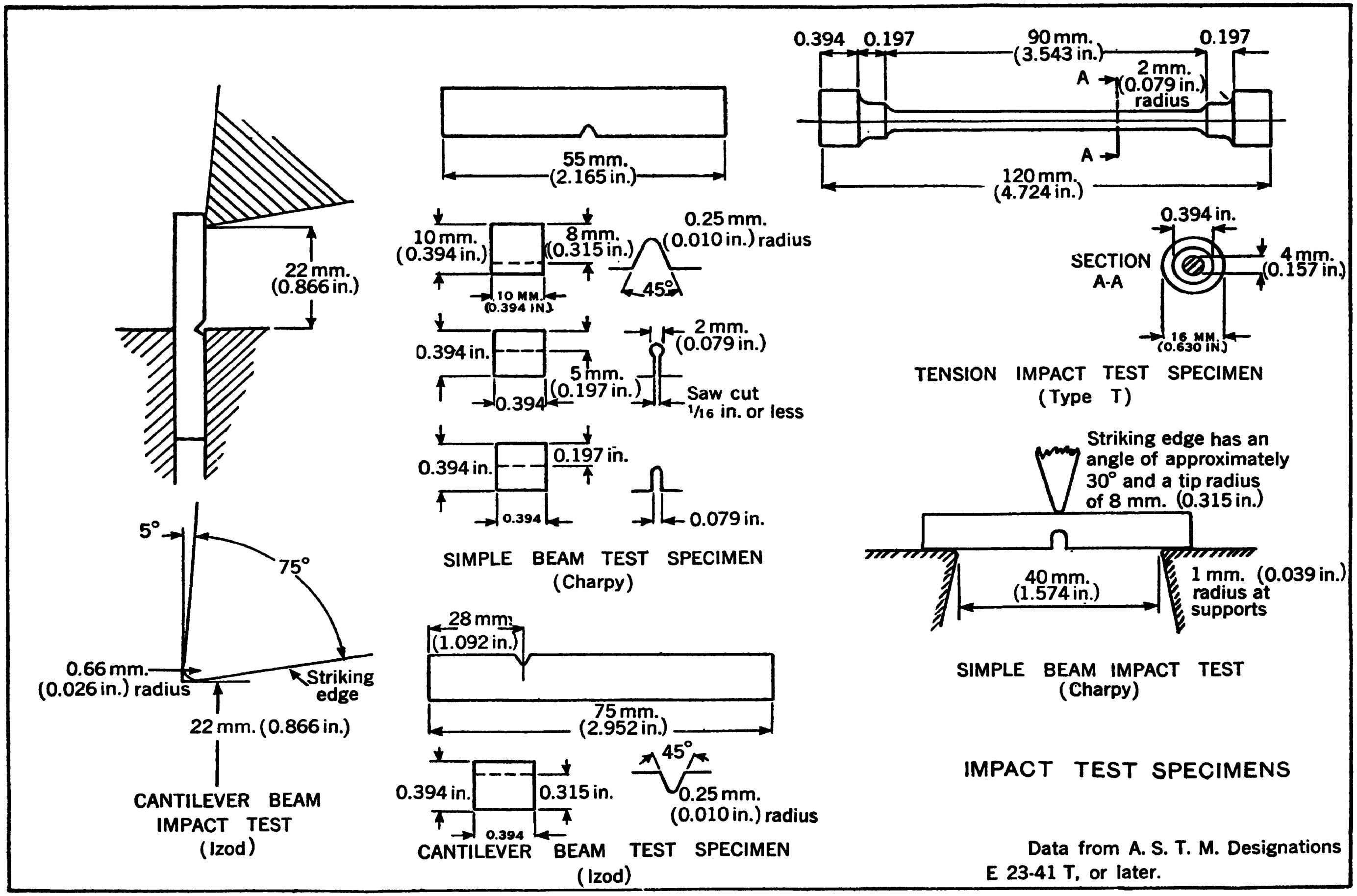


Fig. 66. Standard sizes of impact test specimens.

A more recent development in impact testing is the use of the tension impact specimen as shown in Figures 66 and 67. This type of test, although not standardized, occasionally gives better test results than the beam type. In any event the distribution of stress throughout the impact test specimen is not known and the test results are mainly comparative. They do have some correlation with true stress-strain data, however, as will be shown.

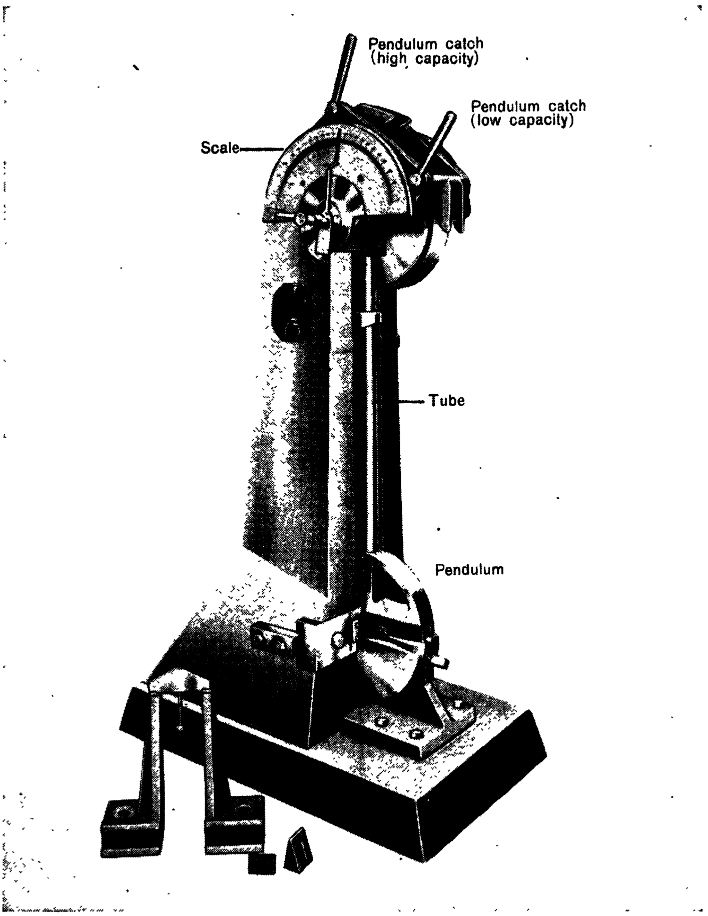


Fig. 67. Essential parts of an impact testing machine. This is a Riehle combination Izod and Charpy tester. The tension impact apparatus is shown at lower left. Specimen, when mounted on crossbar shown and fitted into back of pendulum, is fractured when crossbar strikes projecting catch. (Courtesy American Machine and Metals, Inc., Riehle Testing Machine Division)

The impact experiment is intended to give the student an understanding of the difference in physical properties of a material when compared to static test results. An additional knowledge of the impact testing machine and the manner of testing should also be obtained.

EXPERIMENTAL PROCEDURE

APPARATUS—Charpy or Izod impact testing machine, stopwatch, 36-in. scale, and micrometers.

MATERIAL—Steels of varying ductility (the steels used in Experiment 3 are excellent for this test), malleable iron, gray cast iron, or any other materials covering the range from extremely ductile to brittle metals.

In order to use the impact machine it is necessary to evaluate certain constants which are characteristic for each different machine. These include distance from center of rotation to center of percussion of the pendulum head, the initial potential energy with the pendulum in its starting position, and the correction for lost energy due primarily to friction. While the scales for final test results are given for direct reading machines, as in Figure 67, it is extremely helpful to the student for a full understanding of the impact test and its limitations to make the subsequent analysis.

The weight,* W, of the pendulum is .... lb. and the distance from its center of rotation to its center of gravity,* R_g, is .... ft. The horizontal distance between the points of support for the simple beam specimens, or from the clamp to the point of impact for the cantilever specimen, should conform to the dimensions given in Figure 66.

From a study of physics, the period, T, of a pendulum is for small angles of swing dependent upon the distance from the center of rotation to the center of percussion, L. The *center of percussion* is defined as that point on the striking edge of the pendulum where a normal force may be applied (the blow delivered to the specimen) without producing a reaction at the *center of rotation* (pendulum support). In effect is it that point in the moving pendulum where the dynamic mass may be considered concentrated. It is necessary that the specimen be struck by the center of percussion of the pendulum to receive the maximum energy of blow and to avoid damage to the arm of the pendulum. The relationship for the pendulum may be written

$$T = 2\pi\sqrt{L/g}$$

in which g is the acceleration due to gravity. Reducing and solving for L,

$$L = 0.81T^2$$

in which the units for L are feet and for T, seconds. To determine T the pendulum should be allowed to swing through only a small angle, not over 10° to 15°. Determine the time required for 100 complete oscillations. Make several determinations to obtain a satisfactory average.

---

* If time permits, these values may be determined by the class. Otherwise they should be given by the instructor.

Average value of $T =$ .... seconds.

The distance from the center of rotation to the center of percussion is then

$$L = 0.81T^2 = 0.81\ (\ldots\ldots\ldots\ldots)^2$$

$$L = \ldots\ldots\ldots\ldots\text{ft., or}\ldots\ldots\ldots\ldots\text{in.}$$

The impact strength is taken as the energy absorbed in breaking the specimen and is equal to the difference between the energy in the pendulum blow at the instant of impact with the specimen and the energy remaining in the pendulum after breaking the specimen. Neglecting losses, the kinetic energy of the pendulum at the instant of impact results from, and is equal to, the potential energy possessed by the pendulum at its initial elevation. Similarly, and again neglecting losses, the kinetic energy of the pendulum immediately after breaking the specimen results in, and is equal to, the potential energy acquired by the pendulum at the maximum elevation to which it swings after breaking the specimen. The energy absorbed by the specimen, or the impact strength, neglecting friction, vibrational or other losses, is therefore the difference in the energy of elevation of the pendulum in its initial position and in the position it attains after breaking the specimen. When the pendulum is moved from the position of rest to the fixed initial position the center of gravity rises and energy is therefore imparted to the pendulum. Referring to Figure 68,* determine first the initial angle, a, as the average of three readings

$$a = \ldots\ldots\ldots\ldots\text{degrees}$$

Then the initial height, H, of the pendulum's center of percussion will be

$$H = R_g\ (1 - \cos a)$$

$$H = \ldots\ldots\ldots\ldots(1 - \ldots\ldots\ldots\ldots) = \ldots\ldots\ldots\ldots\text{ft.}$$

and the potential energy

$$E_p = WH = \ldots\ldots\ldots\ldots$$

$$E_p = \ldots\ldots\ldots\ldots\text{ft.-lb.}$$

The energy lost in friction and windage of the pendulum and in friction in the recording mechanism, if not corrected for, will be included in the energy loss attributed to breaking the specimen and therefore erroneously high values of impact strength will be obtained. The total value of these losses on a full swing of the pendulum may be determined by operating the machine as in a test but without a specimen. Raise the pendulum to the initial position through the angle a. Release the pendulum and allow it to swing freely until it reaches the maximum height shown in Figure 68. This position will be slightly below the initial position due to the energy loss. Determine the angle b' to this position as the average of three readings

---

* **When studying the impact machine, reference should again be made to A.S.T.M. Designation E23-41T, or later.**

b' = ...degrees.

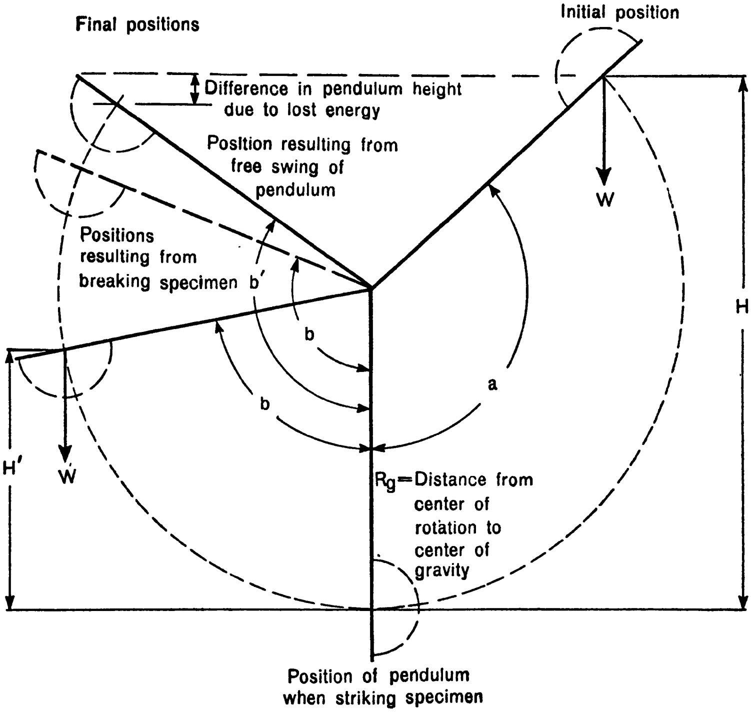

Final positions
Initial position
Difference in pendulum height due to lost energy
Position resulting from free swing of pendulum
Positions resulting from breaking specimen
b'
b
b
a
W
W
H
H'
Rg=Distance from center of rotation to center of gravity
Position of pendulum when striking specimen

FIG. 68. Study of the impact pendulum.

The height of the center of percussion in this position is then

$$H = R_g\,(1 - \cos b')$$

H = ...(1 − . . . .) = ...ft.

and the energy

$E'_f = WH$ = ...

E'_f = ...ft.-lb.

The energy lost is then

$E_p - E'_f$ = ...ft.-lb.

and the energy loss, F, per degree of swing is

$$F = \frac{E_p - E'_f}{a + b'} = \ldots\ldots\ldots\ldots$$

F = ...ft.-lb. per degree.

The kinetic energy with which the pendulum strikes the specimen will then be $E_p - aF$ and is a constant for the machine, neglecting wear and change of temperature.

Likewise, the residual energy remaining in the pendulum, after striking a specimen and swinging through the angle b, is

$$E_f = WR_g\,(1 - \cos b).$$

The residual energy must also be corrected for friction since the pendulum would rise through a slightly greater angle had it not been for such loss. Therefore,

$$E_f \text{ (corrected for friction)} = E_f + bF.$$

The impact strength is the kinetic energy minus the residual energy corrected for friction.

When this study has been completed measure the specimens provided and record the dimensions on the data sheet. Adjust the height of the support so that the center of gravity of the specimen is struck by the center of percussion of the pendulum. Test the specimens, preferably two for each material, and record the results. Examine the fractures and notice the similarity to the fresh fractures studied for grain size, etc., in Experiment 3. Notice also that the ductile material necks down some at the region of the notch. Some characteristic impact fractures are shown in Figure 69.

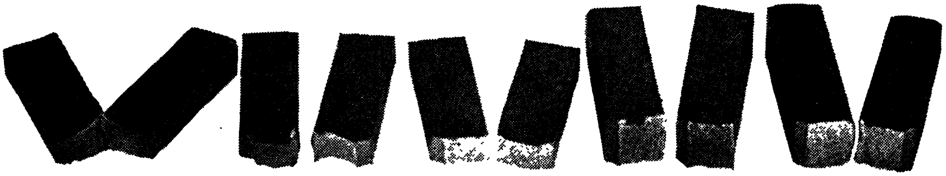


FIG. 69. Impact specimen fractures for (*left to right*) 0.10, 0.30, 0.60 per cent carbon steel, malleable iron, and gray cast iron.

PREPARATION OF REPORT

COMPUTATIONS

The results of all calculations may be indicated on the data sheet.

GRAPH SHEET

If time permits, the complete true stress-strain diagrams should be obtained for the three steels tested in Experiment 3 and used in this experiment. The fracture energy as represented by the total area under these true stress-strain diagrams should be obtained by the student or may be furnished by the instructor. True fracture energy for

low carbon steel = ... in.-lb. per cu.in.
medium carbon steel = ... in.-lb. per cu.in.
high carbon steel = ... in.-lb. per cu.in.

EXPERIMENT 7

IMPACT TESTS

____________________Impact Tester

Name____ Date__________________________

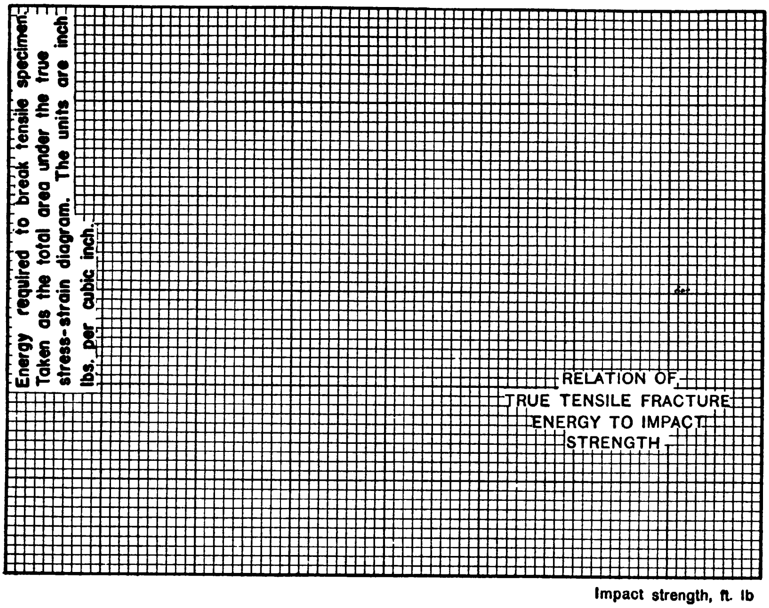
1. Material										
2. Type of specimen*										
3. Specimen dimensions, in.										
4. Cross-sectional area, sq. in. (If specimens differ)										
5. Distance from supports to axis of rotation, in.										
6. Initial angle *(a)*										
7. Potential energy, E_p, neglecting friction, ft.-lb.										
8. Correction for friction, *(F)*. *(a)*, ft.-lb.**										
9. Kinetic energy = potential energy corrected for friction, ft.-lb.										
10. Final angle *(b)*										
11. Residual energy, E_f, neglecting friction, ft.-lb.										
12. Correction for friction, *(F)*. *(b)*, ft.-lb.**										
13. Residual energy corrected for friction, ft.-lb.										
14. Impact strength (line 9-line 13), ft.-lb.										
15. Average of values in line 14.										

***If notched, state type of notch. Otherwise indicate as round, unnotched, etc.**

****Unit value of correction for friction,____________ft.-lb. per degree.**

Sample data sheet for Experiment 7.

On cross-section paper similar to the sample curve sheet shown, plot the relationship of this true fracture energy to the impact strength. Select proper coordinate scales to show this relationship clearly. It should be noted that, while this relationship holds for steels as much alike as these, it may not be true when widely different steels or widely different materials are compared. This is due to the fact that the "notch-sensitivity" of the materials may vary and must be considered. The tension impact test provides results which may be correlated with true fracture energy for a greater variety of materials.



Sample sheet of cross-section paper for Experiment 7 to show the relation of true tensile fracture energy to impact strength. Coordinate scales to be selected and filled in.

DISCUSSION

because distribution of stress is not known

1. Are the results of an impact test absolute or comparative? Why?
2. What physical quality of a material is determined with the impact test?
3. Fill in the following table.

Material	Static tensile strength, psi.	Ductility		Apparent fracture energy *	Average impact strength
		Elongation in 2 in., per cent	Reduction in area, per cent		

---

* Computation 6, Experiment 3.

Is the tensile strength alone a good indication of impact strength? Why?
Is the ductility alone a good indication of impact strength for a wide variety of specimens? Why?
Is the apparent fracture energy a good indication of impact strength? How might it be improved?

4. If two machine parts, which are subjected to energy loads, are to be fastened together by bolts of a given diameter, would it be best to use long or short bolts? Why?

EXPERIMENT 8

THE PROPERTIES OF GRAY, WHITE, AND MALLEABLE IRON

When the carbon content of steel is increased, more and more cementite is formed, as explained in Experiment 3. Since cementite is an alloy of carbon and iron the additional carbon is absorbed. The maximum quantity of carbon which will thus combine with slowly cooled iron is theoretically 1.7 per cent. Beyond that value the carbon is precipitated out of solution, since not more than 1.7 per cent can combine, and is found in the resulting metal as *graphite,* an allotropic form of carbon. The gray color of the graphite flakes is revealed in a fresh fracture and gives gray cast iron its name. In design work gray cast iron is used for massive parts which must withstand compressive stresses. It is not satisfactory for tension, particularly where energy loads might be encountered, due to its lack of ductility and thus fracture toughness, as will be shown in this experiment.

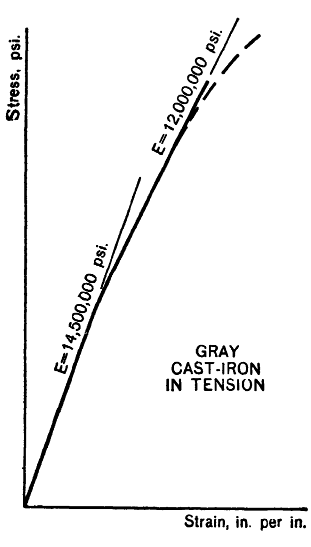


FIG. 70. Modulus of elasticity of gray cast iron decreases with increased stress.

It is difficult to design cast iron parts where deflections must be forecast. This is due to the changing modulus of elasticity as evidenced by the slope of a tangent to the stress-strain diagram as shown in Figure 70. It is customary to state the modulus of elasticity at some stress rather than give an average value.

If gray cast iron is heated and suddenly cooled the carbon stays combined with the iron and the resulting material is largely cementite. It is called white iron because of the near-white, bright appearance which the cementite gives to a fresh fracture. The large amount of cementite present makes white cast iron an extremely hard product which has no ductility. It is used where severe wear must be resisted, in such instances as the face plates of a rock crusher, elbows in pipes carrying powdered coal, sandy water or other materials which tend to scour the conduit at a point of change in flow direction, and for the wearing surface of chilled iron railroad car wheels.

When white cast iron is reheated to the temperature where changes of internal structure can take place, and then carefully cooled to room temperature, a product, *malleable iron,* is produced. It is the same as gray iron with the exception of the form in which the carbon is present. In gray iron it is present as large flakes of graphite which cause weakness in tension. In malleable iron, however, the graphite flakes are broken down to tiny nodules called temper carbon. Because of their small size the nodules of temper carbon do not interfere with the ductility and strength of the iron crystals present to the same extent as do the larger graphite flakes. Malleable iron, therefore, has greater strength and ductility than the other irons.

In conducting this experiment, the student should realize that all three types of iron, for a given carbon content and alloying elements, are the same when analyzed chemically. The only difference is in the form in which the carbon is present. That this has considerable effect upon physical properties of interest to the designer will be shown in this experiment.

EXPERIMENTAL PROCEDURE

APPARATUS—Universal testing machine, extensometer (see Experiment 2), compression tool, spherically seated tension bolts, flat and pointed micrometers, 12-in. scale, dividers, gage punch, and hammer.

MATERIAL—Machined tension and compression specimens of gray cast iron should conform to A.S.T.M. Designations A48-41 (or E8-40T) and E9-33T, or later for all, for specimen size for cast iron. The specimen for malleable iron should conform to Designation A47-33, or later, for size. Any piece of white cast iron can be used but, if time permits, a specimen conforming to E8-40T (shouldered end specimens) should be tested.

The white cast iron may be tested by placing it in a vise and striking the projecting portion suddenly with a hammer. The brittleness of the material will be apparent. If a shouldered end specimen is used, test it for ultimate strength, elongation, and reduction in area.

To perform the extensometer tension test of gray cast iron, follow the instructions given for mild steel in Experiment 2, starting with a small initial load which must subsequently be corrected to zero. Record all data on a data sheet similar to the sample shown. When the unit stress in the specimen is between 15,000 and 18,000 psi. remove the extensometer and continue the test to failure. Note the lack of ductility as evidenced by the amount of elongation and reduction in area. A characteristic fracture for gray iron in tension is shown in Figure 13 for brittle materials in tension. If the extensometer test is not made and a simple tension test is substituted for it, the data may be recorded on a data sheet similar to the second sample shown.

The malleable iron should be tested following the four-point type of commercial test. Measure the specimen and place 2-in. gage marks on the reduced section. Since the standard malleable iron specimen is short it is necessary to bring the heads of the testing machine close together in order to grip the specimen over the entire end section. Be careful that the movable head does not touch the fixed head due to coasting or lack of attention by the operator. The drop of beam indicating the yield point of the malleable iron may not be very pronounced. Supplement this observation with dividers and, if the drop of beam is missed, the yield point load may be secured by the divider method. Determine the maximum load, elongation in 2 in., reduction in area, and the fracture type and record this information on the data sheet.

EXPERIMENT 8

EXTENSOMETER TENSION TEST OF GRAY IRON

Extensometer____________________

Name____________________ Date____________

Machine Loads		Dial Readings, Divisions				Elongations	
Total lb.	Unit stress, psi.	1	2	Average	Corrected to zero	Total, in.	Unit, in./in.

Original diameter =
Original area =
Gage length of extensometer =

Final diameter =
Final area =
Elongation in 8 in.
Elongation in 2 in. =

Type of fracture ____________________

Sample data sheet Number 1 for Experiment 8.

When the compression specimen is placed in the compression tool provision should be made to catch the particles which may fly out when the specimen breaks. After measuring the specimen it should be loaded to failure and the data recorded.

PREPARATION OF REPORT

STRESS-STRAIN DIAGRAM

After the data has been converted to stress and strain, the diagram showing the relationship of the two should be plotted on cross-section paper similar to the sample shown. Draw tangents to the curve at stresses of 5000 psi. and 10,000 psi., with which to determine tangent moduli.

EXPERIMENT 8

PROPERTIES OF GRAY, WHITE AND MALLEABLE IRON

______________________ Date__________

COMPRESSION TEST OF GRAY IRON

Original diameter, in. ______________
Original cross-sectional area, sq. in. ______________
Original length, in. ______________
Maximum load, lb. ______________
Compressive strength, psi. ______________
Fracture type ______________

TENSION TEST OF GRAY IRON

Original diameter, in. ______________
Original cross-sectional area, sq. in. ______________
Maximum load, lb. ______________
Tensile strength, psi. ______________
Elongation in 2 inches, in. ______________
Percentage elongation in 2 in. ______________
Final diameter, in. ______________
Final cross-sectional area, sq. in. ______________
Percentage reduction in area ______________
Fracture type ______________

TENSION TEST OF MALLEABLE IRON

Original diameter, in. ______________
Original cross-sectional area, sq. in. ______________
Load at yield point, lb. { By dividers ______________
By drop of beam ______________
Unit stress at yield point, psi. ______________
Maximum load, lb. ______________
Tensile strength, psi. ______________
Elongation in 2 inches, in. ______________
Percentage elongation in 2 in. ______________
Final diameter, in. ______________
Final cross-sectional area, sq. in. ______________
Percentage reduction in area ______________
Fracture type ______________

Sample data sheet Number 2 for Experiment 8.

COMPUTATIONS

From the stress-strain diagram or experimental data calculate the following:

1. Moduli of elasticity at a stress of 5000 psi. and 10,000 psi.
2. Ratio of compressive strength to tensile strength for gray cast iron.

DISCUSSION

1. Account for the difference in tensile and compressive strengths as indicated by computation 2.

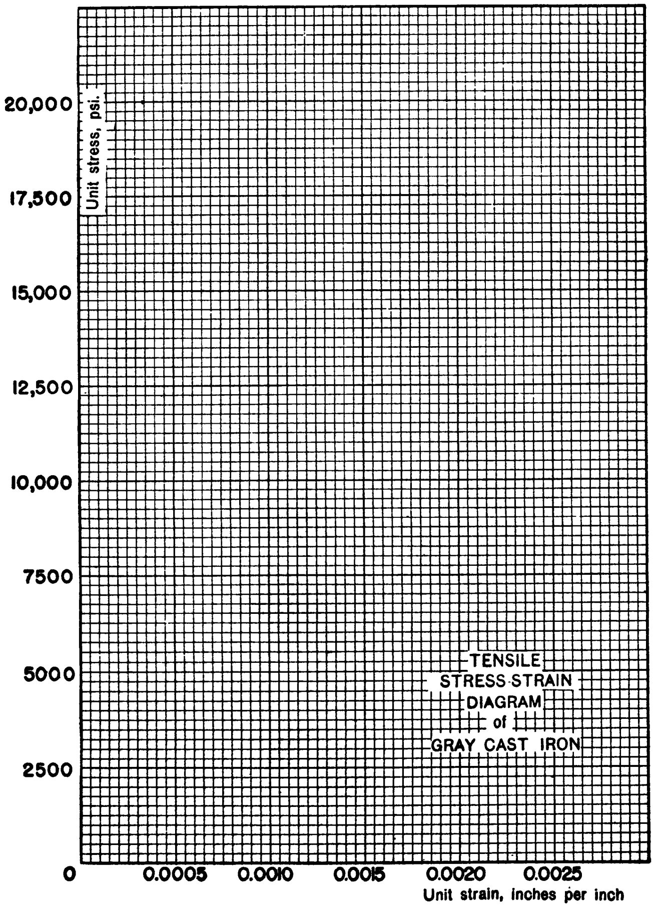
2. In the following table compare the results of this test with A.S.T.M. Designation A47-33, or later, for malleable iron castings:

	Test results	A.S.T.M. Specification *	Does specimen pass or fail this requirement?
Tensile strength, psi.			
Stress at yield point, psi.			
Elongation in 2 in., per cent			

* For Grade No. ....

Would material be accepted? ....

3. Referring to A.S.T.M. Designation A48-41, or later, in what tensile strength classification should the gray cast iron be placed?



Sample sheet of cross-section paper for tensile stress-strain diagram of gray cast iron in Experiment 8, showing coordinate scales.

4. Complete the following comparative table for gray, white, and malleable cast iron by filling in where necessary:

		Gray Iron	White Iron	Malleable Iron
Chemical analysis (unalloyed)		Iron and carbon	Iron and carbon	Iron and carbon
Metallurgical properties		Free carbon in the form of large flakes of graphite	Cementite or combined carbon	Free carbon in the form of tiny nodules of temper carbon
Design Properties	Tensile strength, psi.			
	Yield point, psi.	None	None	
	Elongation, per cent		None	
	Tensile modulus of elasticity, psi.		20,000,000	25,000,000
	Brinell hardness	180	480	140

EXPERIMENT 9

TENSION TEST OF NON-FERROUS METALS

Most test specimens of aluminum, copper, brass, bronze, zinc and other non-ferrous metals are of the 2-in. gage length type. They may be round or flat, depending upon the dimensions and shape of the section from which they were cut. It is for this size of specimen that the autographic electrical extensometer is more commonly adapted in routine testing. The mechanical extensometers of small gage length, such as those shown in Experiment 2, are used when the autographic recorders are not available. Since most non-ferrous metals, with the exception of a few bronzes, have no yield point it is necessary to obtain the stress-strain diagram and from it the yield strength. In commercial routine testing it is customary not to convert the observed data to stress and strain but rather to plot a load-elongation diagram. From this diagram the load at the yield strength may be found in the usual way by converting the specified offset to dial divisions for the gage length used. This single value of load is then converted to stress. The method is obviously much quicker.

The following values of offset taken from various A.S.T.M. Standards and Tentative Standards and summarized in A.S.T.M. Designation E6-36, or later, should be used to select the offset for each material tested in this experiment:

Standards or Tentative Standards for:

Alloy-Steel Pipe	0.2 per cent "offset"
Aluminum-Alloy Bars, Rods, Shapes, Sheet	
Magnesium-Base Alloy Forgings, Castings, Sheet	
Copper-Silicon Alloy Plates, Sheets, and Bars	0.5 per cent elongation under load (approximately equivalent to 0.35 per cent "offset")
Malleable Iron Castings	
Aluminum-Bronze Castings	
Bronze Bearing Metals and Steam or Valve Sand Castings	
Composition Brass or Ounce Metal Sand Castings	
Naval Brass Rods for Structural Purposes	

When a yield point exists in a bronze material it may be found by the drop of the beam method. The beam drop is not very pronounced, however, due to the sudden response of the material to the cold-working which takes place. For this reason it is easily missed and it becomes necessary to resort to the divider method to indicate the yield point. In commercial testing, when the operator has no help in making the divider determination, another method may be used. A micrometer is placed on the specimen as though measuring it and left hanging in that position. When the yield point is reached the micrometer's C-section will twist downward as it rotates about the loosened stem and anvil. The load necessary to produce this condition is taken as the yield point load.

This experiment is designed to acquaint the student with the physical properties of some of the non-ferrous metals more commonly used in design, and also to illustrate the manner in which commercial extensometer tension tests are performed.

Experimental Procedure

APPARATUS—Universal testing machine, 2-in. extensometer, spherically seated tension bolts, flat and pointed micrometer, 12-in. scale, dividers, gage punch, and hammer.

MATERIAL—Structural aluminum alloy, hard copper, soft copper, bronze, zinc, or any other non-ferrous material.

Examine the extensometer used, its manner of operation, and the inch equivalent of each dial division. Measure the specimen, place two 1-in. punch marks over the gage length, and place it in the spherically seated tension bolts. Apply a small initial load and attach the extensometer to the specimen. Correction to zero load will be made on the graph sheet. The extensometer should be adjusted to give the maximum travel in the direction of the subsequent strain and the dial then set to zero. Apply loads in the increments given by the instructor, recording the reading of the extensometer for each load. Obtain sufficient data in the region of the proportional elastic limit to show reliably the "knee" of the diagram when plotted. When far enough into the plastic range to ensure a permanent set greater than the specified offset, remove the extensometer and continue loading the specimen to failure. Record the maximum load, elongation, etc., on the data sheet and observe the type of fracture.

Preparation of Report

LOAD-ELONGATION DIAGRAM

On cross-section paper similar to the sample shown, plot the load-elongation diagrams (using load and dial divisions) for each material tested. Select proper coordinate scales and fill them in on the graph paper. Correction to zero may be made on this graph when the yield strength is determined. The specified offset should be converted to dial divisions and this offset then taken from where the projected straight-line portion of the diagram crosses the abscissa. Obtain the yield strength load as previously instructed.

TANGENT-MODULUS DIAGRAM

If time permits plot a stress-tangent modulus diagram for aluminum. Note the difference between this diagram and that previously found for steel, or shown in Figure 9.

COMPUTATIONS

From the load-elongation diagrams compute the moduli of elasticity and stresses at the proportional elastic limit for each material tested. The results of all other computations for tensile strength, yield strength, elongation, etc., may be shown on the data sheet.

EXPERIMENT 9

TENSION TEST OF NON-FERROUS METALS

Name ____________________ Date ____________

Extensometer ____________________ Gage length ____________

Material ______		Material ______		Material ______	
Original diameter, in. ______ Original area, sq. in. ______		Original diameter, in. ______ Original area, sq. in. ______		Original diameter, in. ______ Original area, sq. in. ______	
Load, lb.	Dial divisions	Load, lb.	Dial divisions	Load, lb.	Dial divisions
Final diameter, in. ______ Final area, sq. in. ______ Elongation, in. ______ Elongation, per cent ______ Tensile strength, psi. ______ Yield strength, psi. ______ Area reduction, per cent ______ Fracture type ______		Final diameter, in. ______ Final area, sq. in. ______ Elongation, in. ______ Elongation, per cent ______ Tensile strength, psi. ______ Yield strength, psi. ______ Area reduction, per cent ______ Fracture type ______		Final diameter, in. ______ Final area, sq. in. ______ Elongation, in. ______ Elongation, per cent ______ Tensile strength, psi. ______ Yield strength, psi. ______ Area reduction, per cent ______ Fracture type ______	

Sample data sheet for Experiment 9.

Sample sheet for cross-section paper for tensile load-elongation diagram of non-ferrous metals in Experiment 9. Note that load is plotted against extensometer readings without converting to stress and strain. Coordinate scales to be filled in.

DISCUSSION

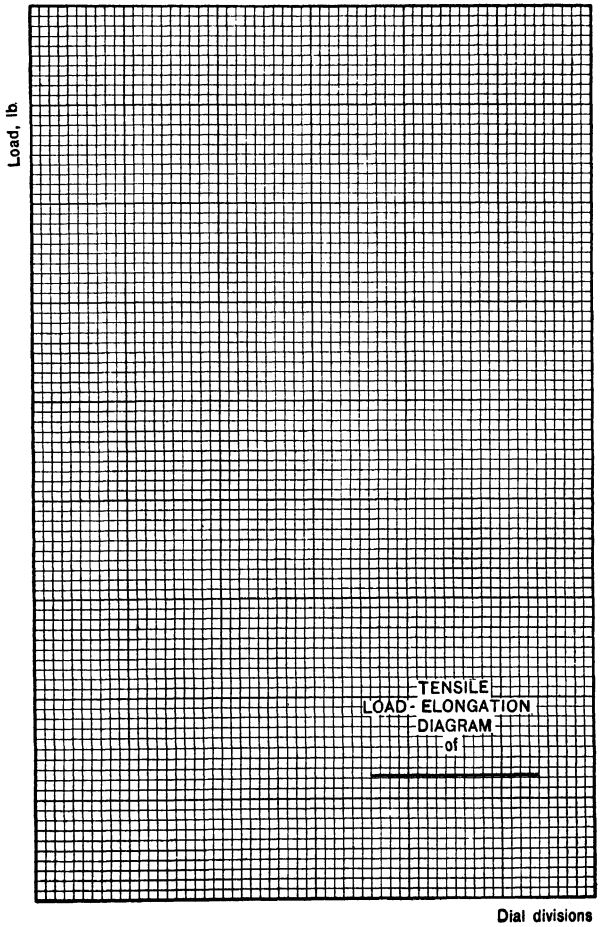
1. Use a table similar to the following for each material to compare the test results with appropriate A.S.T.M. specifications or average values given by the instructor:

   Material ....

	Test results	A.S.T.M. specification *	Does specimen pass or fail this requirement?
Yield strength (offset = per cent), psi.			
Tensile strength, psi.			
Elongation in 2 in., per cent			

* A.S.T.M. Designation..................

Would this material be accepted? ....



2. Compute the modulus of elastic resilience, E_R, for each material and compare with that obtained for the steel in Experiment 2.

Material	Modulus of elastic resilience, in.-lb./cu. in.	Ratio. E_R of this material to E_R of steel *

* Modulus of elastic resilience for structural steel, Experiment 2, ...

3. Using the method explained in Experiment 2, complete the metal-working problem for aluminum outlined below, using the same dimensions of plate, amount of working, and time of working used for steel. Note differences in the two materials. Refer again to Figure 38 if necessary.

Problem. Given a plate .... in. long, ... in. wide, and .... in. thick of the same aluminum as tested in this experiment. Determine the total force required to cold-work this plate a specified amount, the distance the movable jaw must move during this operation, and the horsepower required to complete the operation in a specified time.

Total Force. It is required that the plate be cold-worked to a unit stress of .... psi. What total force must be exerted by the hydraulic system to fulfill this requirement?

Total Movement of Jaw. It is specified that the plate be stretched to a point where the permanent set (cold-working) is .... per cent. Through what distance must the movable jaw travel to fulfill this requirement? (Remember that the material springs back some after release of load.)

Horsepower Required. By counting the squares under the stress-strain diagram, and by converting these squares, on the basis of the scales used, to energy expended, it is possible to determine the total energy required to deform the plate a specified amount. When this energy must be expended in a certain time, the horsepower may be calculated.

It is specified that the plate be stretched to a point where the permanent set (cold-working) is .... per cent and that this stretching be accomplished in .... seconds. Determine the horsepower required to accomplish this. No factor of safety need be used.

(a) Total energy as the area under the stress-strain diagram at the specified permanent set. .... in.-lb. per cu. in.

(b) Total energy required for this plate. .... in.-lb.

(c) Horsepower required to complete operation in .... seconds. (One horsepower is equivalent to 550 ft.-lb. per second.)

EXPERIMENT 10

THE PHYSICAL PROPERTIES OF LAMINATED PLASTICS

Rapid progress and considerable improvement have been, and are being, made in the manufacture of plastics to improve their physical properties and thus their adaptation to structural and mechanical applications. In airplane design, plastic parts are often more desirable than metallic parts because of the ease and intricacy with which they can be formed or molded and yet possess a favorable strength-weight or stiffness-weight ratio. When used for gears, laminated plastics have superior wear resistance as well as the advantage of quiet operation. Some applications of plastics are shown in Figure 71.

Plastics are classed either as *thermoplastic* or as *thermosetting.* The former class will soften when heated or become rigid when cooled. They are seldom used for stress-carrying parts, due to poor shock resistance, particularly at low temperatures. The thermosetting class of plastics set upon the application of heat, due to polymerization (the manner in which the molecular weight of a substance may be increased). The increase in molecular weight is evidenced externally by better physical properties. Thermosetting resins may be combined with wood, paper, cloth, mica, and asbestos to provide still greater strength, heat resistance, etc. Most stressed industrial parts are of this class. The general types or groups of plastics are:

1. Cellulose acetate: thermoplastic
2. Polymethyl methacrylate: thermoplastic
3. Polyvinyl acetals: thermoplastic
4. Phenol formaldehyde: thermosetting
5. Urea formaldehyde: thermosetting
6. Casein: thermoplastic (some types may actually be set cold)

The laminated phenol formaldehyde (commonly called phenolic) plastic products probably are more commonly used. An outline of the method by which they are produced is shown in Figure 72. Since cloth is woven with the heavy thread (warp) in the long direction of the roll, it may be laid after impregnation so that the heavy threads are all parallel and the resulting plastic product is considered to have grain. Considerable difference in physical properties for longitudinal and transverse test specimens may be observed. If the direction of the grain is alternated on successive layers no difference in strength exists.

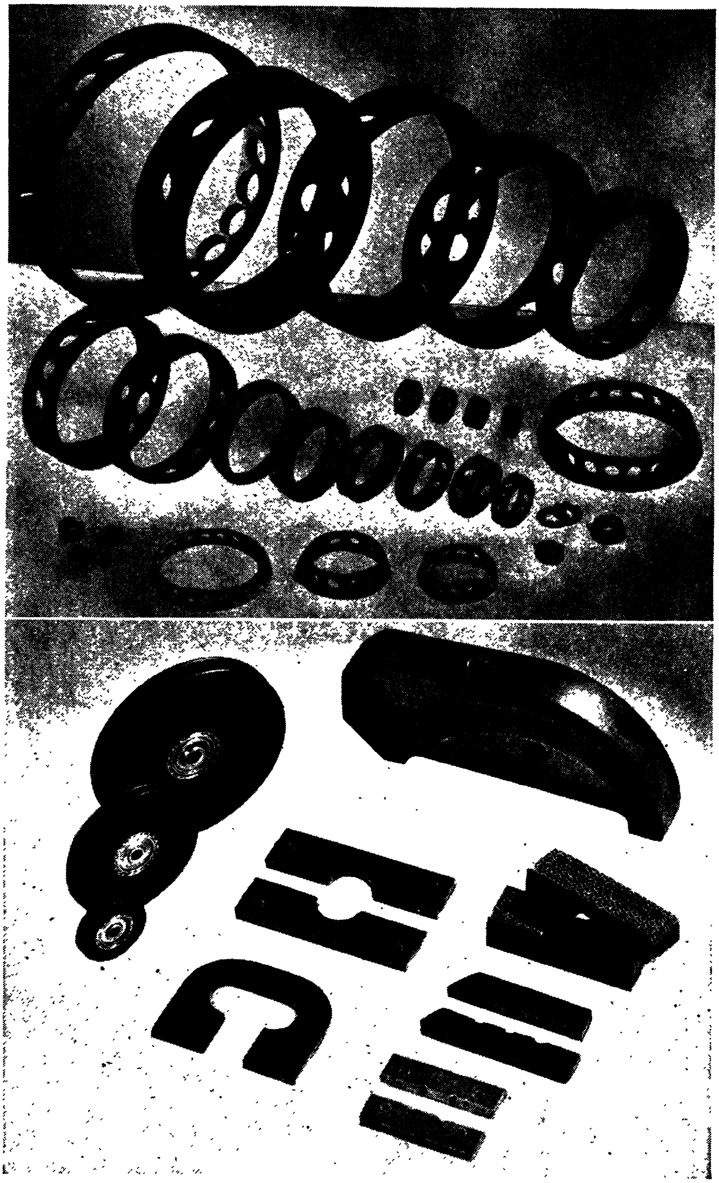


FIG. 71. A few of the many applications of plastics for industrial parts. Above are various sizes of cages to align the balls in a ball bearing. Below are pulleys, cable guides, and fairing parts for aircraft. (Courtesy of Bakelite Corporation)

This experiment is designed to give the student contact with the behavior of plastics in tension and compression, and a comparison of their properties with those of other engineering materials. The tenacity of the bond between layers will also be obtained.

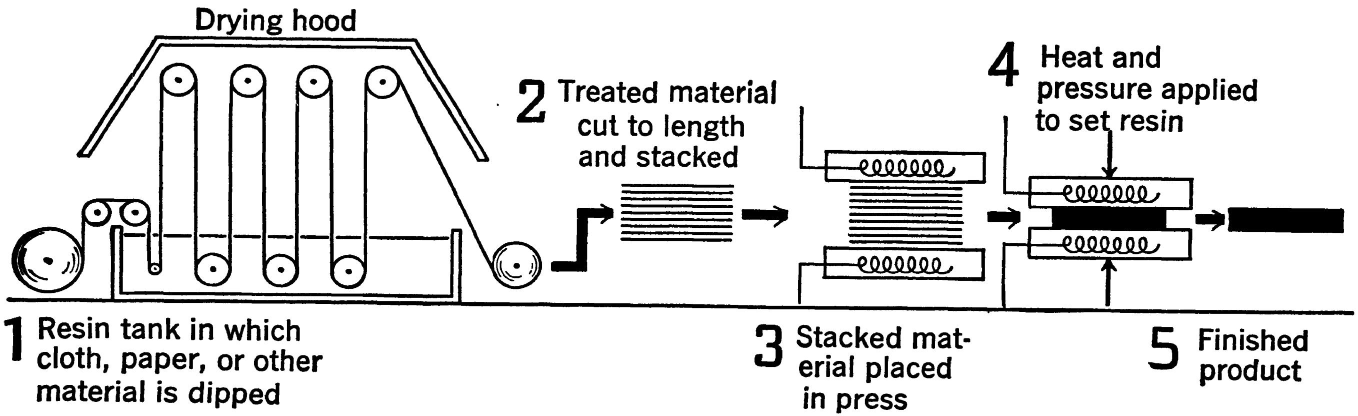

Drying hood
1 Resin tank in which cloth, paper, or other material is dipped
2 Treated material cut to length and stacked
3 Stacked material placed in press
4 Heat and pressure applied to set resin
5 Finished product

Fig. 72. Steps followed in manufacturing a laminated plastic.

EXPERIMENTAL PROCEDURE

APPARATUS—Universal testing machine, compression tool, 10-mm. diameter hard steel ball, flat micrometers, 12-in. scale, dividers, punch, and hammer.

MATERIAL—A laminated cloth plastic of the phenolic or urea type from which tension, compression, and bond strength specimens have been cut conforming to A.S.T.M. Designation D229-42, or later.

Measure all specimens and record the dimensions on the data sheet. If specimens with a definite direction of grain are tested be careful that the cross section which is to take load is measured. Place punch marks over the gage length of the tension specimen and grip it securely in the flat grips. Attach a 2-in. extensometer and adjust it for maximum travel, setting the dial to zero. Apply a load equivalent to a unit stress of 5000 psi. and note the elongation under load at this point. Remove the extensometer and increase the load until the specimen breaks, noting the load and type of fracture as well as the fact that the cross section has not been reduced in area. Place the broken ends of the specimen together and observe that the final elongation has no significance; only the elongation under load is important. Repeat this test procedure for all tension specimens.

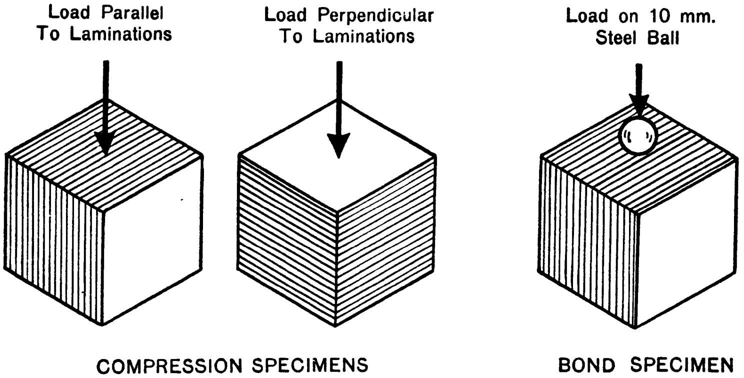


FIG. 73. Method of loading compression and bond specimens of laminated plastic.

Compression specimens should be loaded with respect to the laminations as shown in Figure 73. If specimens having grain are tested, three cubes should be loaded as follows:

1. Load parallel to grain and parallel to laminations.
2. Load perpendicular to grain but parallel to laminations.
3. Load perpendicular to laminations (as in Figure 73).

The compression cubes should be placed in the compression tool and a protective covering placed around them to stop flying particles. Load the specimens to failure, noting the maximum load and manner of failure.

For the bond strength, a 10-mm. diameter hard steel ball should be placed on the specimen as shown in Figure 73 and loaded until a split occurs. The load required to split the cube, divided by the area resisting the load, is the bond strength. This test may be carried out in the compression tool by placing the ball on the specimen and then inserting a moderately hard steel plate between the ball and the upper seat of the compression tool. This latter precaution is necessary to prevent damage to the seat.

Preparation of Report

COMPUTATIONS

The results of all computations are shown directly on the data sheet.

DISCUSSION

1. Plastics are often compared with other materials on the basis of their strength-weight or stiffness-weight ratios. Complete the following table and make this comparison:

Material		Tensile strength, psi.	Modulus of elasticity, psi.	Ratio,[9] s_t/weight	Ratio, E/weight
Plastic tested	tension		1,000,000 [8]		
	compression [1]		1,000,000 [8]		
	compression [2]		1,000,000 [8]		
Structural aluminum [3]					
Structural steel [4]					
Gray cast iron [5]					
Wood in bending [6]					

[1] Load parallel to laminations.
[2] Load perpendicular to laminations.
[3] From Experiment 9.
[4] From Experiment 2.
[5] From Experiment 8.
[6] From Experiment 5.
[7] Taken as the modulus of rupture in bending, Experiment 5.
[8] Average values.
[9] For plastics in compression this ratio will be s_c/weight.

Use the following unit weights:

Aluminum	0.101 lb. per cu. in.
Steel	0.294 lb. per cu. in.
Cast Iron	0.260 lb. per cu. in.

2. Are plastics of the type tested able to resist fracture impact? Explain.

EXPERIMENT 10

PHYSICAL TESTS OF LAMINATED PLASTICS

Name____________________________________ Date_______________

TENSION TESTS

Specimen		
Direction of grain		
Original dimensions, in.		
Original area, sq. in.		
Maximum load, lb.		
Tensile strength, psi.		
Elongation in 2 in. at 5000 psi.		

COMPRESSION TESTS

Specimen			
Original length, in.			
Original dimensions, in.			
Original area, sq. in.			
Maximum load, lb.			
Compressive strength, psi.			
Final length, in.			
Type of fracture			

BOND STRENGTH

Original dimensions, in.______________________________

Original area, sq. in.______________________________

Maximum load, lb.______________________________

Bond strength, psi.______________________________

UNIT WEIGHT

Dimensions of specimen, in.______________________________

Volume of specimen, cu. in.______________________________

Weight, lb.______________________________

Unit weight, lb. per cu. in.______________________________

Sample data sheet for Experiment 10.

EXPERIMENT 11

HARDNESS TESTING

Resistance to indentation, cutting, or scratching, actual toughness, or brittleness are just a few of the ways in which hardness may be evaluated. In spite of the testing equipment available there is not one single hardness test that may be applied without reservation to all materials and yet yield an absolute answer that has real physical concept and meaning. Although several different types of tests are available and are used thousands of times each day, the results obtained may be interpreted only by comparison with other materials tested in the same type of machine. The test results in general (but not always) may be compared with the results obtained on the same specimens in other types of hardness tests, but they are purely comparative and not absolute in the same sense as tensile strength.

The purpose of the hardness test as made by one individual may be to determine if a material will bend plastically in forming. Another individual might use the test to determine a material's wearing qualities. Still another may be interested to learn if a metal is readily machinable or if it is resilient and thus usable for springs. Consequently, it may be seen that the hardness test has a great variety of meanings and interpretations. No attempt will be made here to evaluate the advantages and disadvantages of each type of hardness test or generally to discuss their value and significance but, as hardness tests are of extreme value when properly made and properly interpreted, a study will be made of the manner of testing and the limitations of the results.

The first tests resembling those for hardness were developed for minerals. Various materials were scratched over a rock and if an impression was made on the rock surface the rock was considered to be softer than the other material. The Moh's hardness scale universally used for this work listed various minerals in ten steps of increasing hardness, from talc to diamond. The more commonly used hardness tests employed today operate according to one of the following two principles:

1. Indentation hardness.
   - *a.* Determine the diameter of impression made by an indentor of a standard size, loaded with a standard load, and loaded for a standard length of time.
   - *b.* Determine the depth of impression made by an indentor of a standard size, loaded with a standard load, and loaded for a standard length of time.
2. Resilience or energy hardness—dynamic hardness.
   - *a.* Determine the height of rebound of a standard weight falling through a standard distance.

Hardness tests are only applicable to materials which are essentially homogeneous. Although very few metallic or non-metallic materials fall into this category it is the obviously non-homogeneous materials which are meant here. Metals, such as gray cast iron, malleable iron, and some bearing metals, cannot satisfactorily be tested for hardness. Non-metallic as well as non-homogeneous materials, such as concrete, cannot be tested for hardness. If a small indentor is used and applied at such a point on a metal surface where it contacts a hard particle (in a softer matrix), the result will indicate high hardness. A larger type of indentor in many cases will average the surface condition and give better reproductibility of results.

The use of relatively homogeneous materials for hardness tests is particularly important when the results are to be used in predicting or checking tensile strength. Many formulas for estimating tensile strength from the results of hardness tests have been proposed. Only a few have been accepted as applicable for any but a few limited materials. Some of these will be presented later.

The present experiment is intended to acquaint the student with the more commonly used hardness tests, the technique of testing, the limitations of the results, and their applications. Throughout the hardness tests, the student should refer to A.S.T.M. Designations E10-27 and E18-36, or later for both.

EXPERIMENTAL PROCEDURE

APPARATUS—Brinell hardness testing machine and auxiliary microscope, Rockwell hardness tester, and Shore Scleroscope hardness tester.

MATERIAL—Steels tested in Experiment 3, aluminum, hard and soft copper, gray cast iron, malleable iron and additional special materials given by the instructor. All specimens should be machined and ground flat on the test surface. Care should be taken to see that all specimens conform in size to A.S.T.M. Standards E10-27 and E18-36, or later for both.

When operating hardness testers, never force any part of the operating mechanism. If the tester does not operate satisfactorily consult the instructor. Testers should rest on solid supports free of vibration. If it is doubtful that a material can be tested with one type of indentor or penetrator, use the next harder indentor. This avoids damage to the penetrator.

BRINELL TESTER AND PROCEDURE—The Brinell indentation hardness test is of the diameter of impression type. In Figure 74(a) is shown a modern type of Brinell hardness machine. This tester is automatically and electrically driven but the same principles are involved in the hand operated types. The essential parts are a rigid support for the specimen and means of applying and measuring load, either mechanically or hydraulically. The test procedure consists in applying a known load through a hardened steel ball to the surface of the material to be tested. The diameter of the resulting permanent impression in the metal is measured with a microscope. The Brinell hardness number is found from the following relationship:

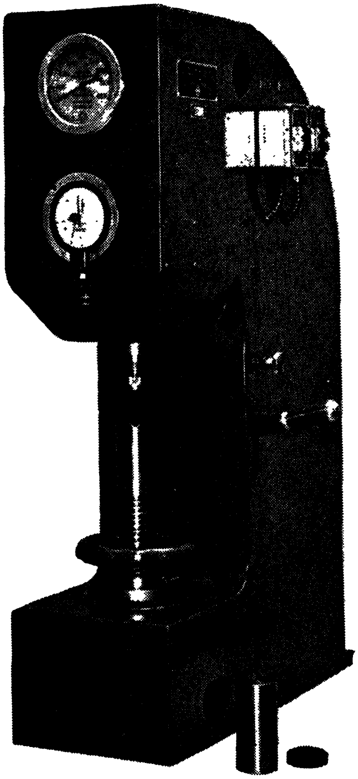


Fig. 74(a). Modern style automatic electrically operated Brinell hardness machine with depth of penetration indicator (*lower dial*). (Courtesy Tinius Olsen Testing Machine Company)

$$\text{B.H.N.} = \frac{P}{\frac{\pi D}{2}\left(D - \sqrt{D^2 - d^2}\right)}$$

in which B.H.N. = Brinell hardness number, kg. per sq. mm.
P = applied load, kg.
D = diameter of steel ball indentor, mm.
d = diameter of impression made in specimen by ball indentor, mm.

It is assumed that the ball indentor remains spherical when applied to the specimen and loaded. Therefore, the surface area of the impression may be assumed to be spherical. That this assumption is not correct should be obvious. Due to the distortion of the ball under load and the elastic springback of the metal when the load is removed, it is necessary to use a standard size of ball and load. A ball 10 mm. in diameter and loads of 3000 kg. for hard metals or 500 kg. for soft metals are required in standard specifications. The test specimens must be of such thickness that no bulge or other marking showing plastic distortion due to the load appears on the side of the test specimen adjacent to the impression.

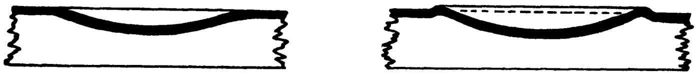

Encircling depression
Encircling ridge

FIG. 74(b). Impressions left in test surface by Brinell ball.

To operate the Brinell machine, place the test specimen on the capstan screw and elevate it until the specimen is in firm contact with the ball. Place the center line of the load far enough from the nearest edge of the specimen so that a straight edge, applied to the side of the specimen adjacent to the point of load, shows no bulging. If the machine is hand operated close the escape valve and operate the pump slowly and steadily until the full pressure is on the specimen as indicated by the floating of the weights. Apply load for 30 seconds,* then open the escape valve slowly and allow the load to decrease to zero. In electrically driven machines this operation is completed automatically. Remove the specimen by lowering the capstan screw. Measure the diameter of the impression with the micrometer microscope to the nearest 0.01 mm. Using the average value of two readings taken at right angles to one another, obtain the Brinell hardness number from Table I given with A.S.T.M. Standard Designation E10-27, or later, and record the value on the data sheet.

The impressions left by the ball in this test are of two characteristic types as shown in Figure 74(b). It is difficult in either case to determine with the microscope the edge of the impression. The depth of penetration, although not fulfilling the original definition of the Brinell hardness test, is a more positive and reliable indication of hardness. Therefore it is becoming more common to make this determination in Brinell tests.

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* Actually a minimum time of 10 seconds for iron and steel and 30 seconds for other metals is specified. It would undoubtedly be more satisfactory to specify the exact holding time for every metal tested.

EXPERIMENT 11

HARDNESS TESTS OF VARIOUS METALS

Name________________________________ Date________________

Specimen number	Scleroscope hardness	Diameter of brinell impression	Brinell hardness	Rockwell hardness *

* Indicate if scale is B or C

Sample data sheet for Experiment 11.

The machine shown in Figure 74(a) is fitted with such a penetration indicating dial. Some disadvantages of the Brinell test are:

1. It cannot be used for very thin specimens.
2. It cannot be used for extremely hard materials due to elastic (or plastic) deformation of the ball.
3. It cannot be used for surface-hardened materials since the depth of penetration may exceed the depth of case.
4. Hardness values of more than 450 to 500 are only broadly comparative.

ROCKWELL TESTER AND PROCEDURE—The Rockwell indentation hardness test is of the depth of impression type. The penetrator used may be a small steel ball or a spheroconical diamond (called a "Brale" penetrator) and the load may be varied from 60 to 150 kg. Various combinations of loads and penetrators may be made and the resulting hardness values thus obtained must be distinguished by providing a separate scale for each combination. These combinations are given in Table I of A.S.T.M. Standard Designation E18-36, or later. Most work can be performed with the B and C scales, representing a 100-kg. load on a $\frac{1}{16}$-in. diameter steel ball and a 150-kg. load on a diamond cone, respectively. Further, these scales are respectively marked in red and black figures.

In Figure 75 is shown a Rockwell hardness tester. The instrument shown in this figure is automatically motor operated. Hand operated machines are also used. The cycle of operation, the steps to be followed in operating the Rockwell tester, and the principles of operation are fully outlined in Figure 76.

Before making the test be certain that the proper penetrator is being used and that the proper load is being applied to that penetrator. Use the tester several times on a piece of scrap material in order to seat firmly the penetrator and the anvil supporting the specimen. This precaution should be taken every time the penetrator or anvil is changed. When the elevating screw brings the work against the penetrator the last movement of the screw should be such that the specimen is being elevated and the dial is moving in the same direction it will move when subsequent load is applied. Never release the elevating screw part way. In bringing the work and penetrator into contact be careful to avoid all impact. The zero position of the pointer is shown by the "set" mark on the face of the dial. When applying the major load, allow the operating handle to move without interference until the major load is completely applied. This may be observed in two ways: (1) by noting when the pointer suddenly slows down; or (2) by watching the weight arm to see that it is completely free from the dash pot control. When the major load has been completely applied, bring the operating handle back to the latched position. See that this is accomplished in less than 2 seconds after the major load is com-

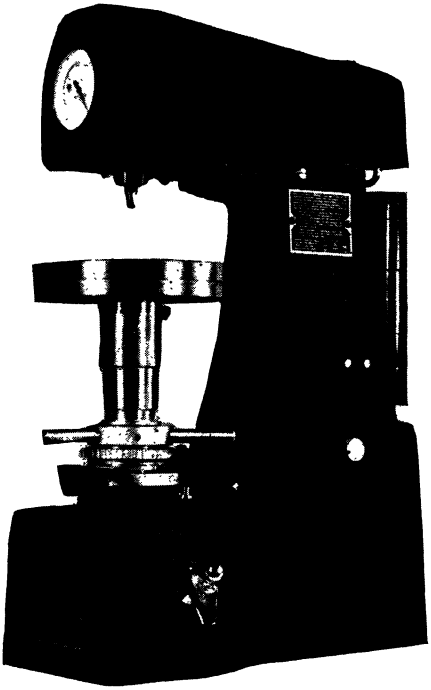


FIG. 75. Electrically driven Rockwell hardness tester. (Courtesy Wilson Mechanical Instrument Co.)

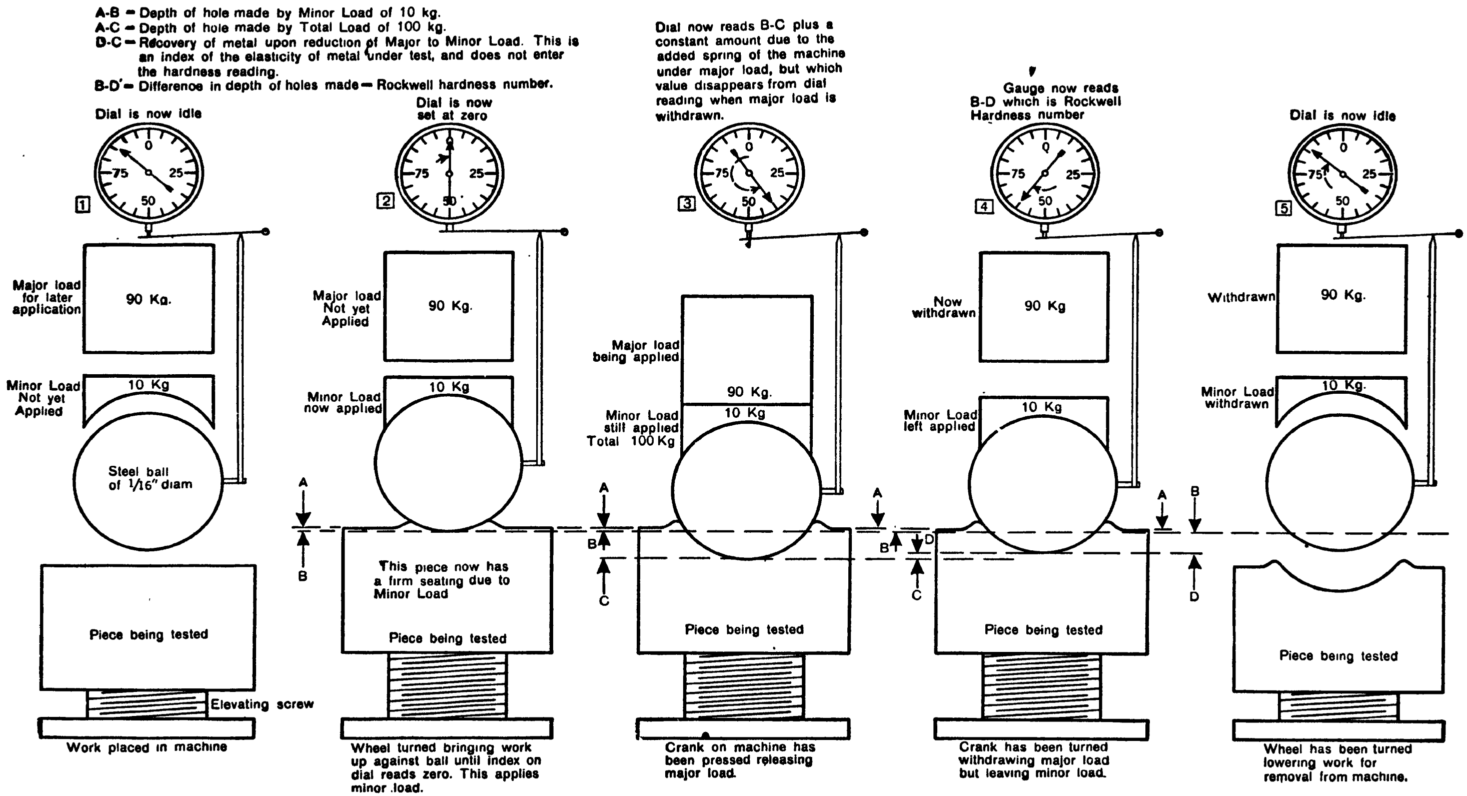

A-B = Depth of hole made by Minor Load of 10 kg.
A-C = Depth of hole made by Total Load of 100 kg.
D-C = Recovery of metal upon reduction of Major to Minor Load. This is an index of the elasticity of metal under test, and does not enter the hardness reading.
B-D' = Difference in depth of holes made = Rockwell hardness number.
1
Dial is now idle
0
25
50
75
Major load for later application
90 Kg.
Minor Load Not yet Applied
10 Kg
Steel ball of 1/16" diam
Piece being tested
Elevating screw
Work placed in machine
2
Dial is now set at zero
Major load Not yet Applied
90 Kg.
Minor Load now applied
10 Kg
A
B
This piece now has a firm seating due to Minor Load
Piece being tested
Wheel turned bringing work up against ball until index on dial reads zero. This applies minor load.
3
Dial now reads B-C plus a constant amount due to the added spring of the machine under major load, but which value disappears from dial reading when major load is withdrawn.
Major load being applied
90 Kg.
Minor Load still applied Total 100 Kg
10 Kg
A
B
C
Piece being tested
Crank on machine has been pressed releasing major load.
4
Gauge now reads B-D which is Rockwell Hardness number
Now withdrawn
90 Kg
Minor Load left applied
10 Kg
A
B
C
D
Piece being tested
Crank has been turned withdrawing major load but leaving minor load.
5
Dial is now idle
Withdrawn
90 Kg.
Minor Load withdrawn
10 Kg.
A
B
D
Piece being tested
Wheel has been turned lowering work for removal from machine.

Fig. 76. Steps to be followed when using the Rockwell hardness tester.

The cycle of operation is diagrammatically shown here to illustrate the principle of operation and to show the action of the ball under application and release of minor and major loads. The size of the ball has been greatly exaggerated. Note that the dial is divided into 100 divisions. Each such division is one point on the hardness scale and is equivalent to 0.002 mm. of motion of the penetrator. The scale of the dial is reversed so that a deep impression gives a low reading, indicating low hardness and conversely for a shallow impression. (Courtesy Wilson Mechanical Instrument Co., with slight revisions by the author) pletely applied. The Rockwell hardness is taken as the reading of the pointer on the proper dial after the major load has been removed and while the minor load is still applied. All readings must be prefixed by the proper letter, showing which scale was used. The B scale should be used for hardness values from 0 to 100 and the C scale for harder materials. Hardness values within two divisions of one another are considered the same. Average hardness numbers should be given to the nearest whole value.

For material thinner than about 0.05 in. the Rockwell Superficial Hardness Tester is used. The same principle of operation is employed as for the tester just explained but smaller loads are used and the depth-measuring device is more sensitive. It is used principally for slightly surface-hardened material and for very thin sections of spring steel and metal sheets.

SHORE SCLEROSCOPE TESTER AND PROCEDURE—The Shore Scleroscope hardness tester is of the dynamic type. The apparatus for making this type of test is shown in Figure 77. The scleroscope test is made by dropping a diamond tipped hammer on the metal to be tested and noting the height of rebound of the hammer. A glass tube holds the hammer and serves as a guide for it. The hammer is raised to the top of the tube by air suction and maintained there by a mechanical catch. A hand bulb furnishes the air to actuate the various functions in rotative order. Carefully plumb the glass tube by means of the vertical rod and attached leveling screws. This prevents friction between the hammer and the glass tube. Raise the hammer by means of the hand bulb, place the specimen on the support, and then lower the glass tube and its housing by means of the rack and pinion until contact is made. By again squeezing the bulb the hammer is released without giving it initial velocity. The hammer falls, strikes the specimen, and rebounds. The height of rebound of the top of the hammer is noted on a scale divided into 140 arbitrary equal parts and located in back of the glass tube. Raise the glass tube and re-

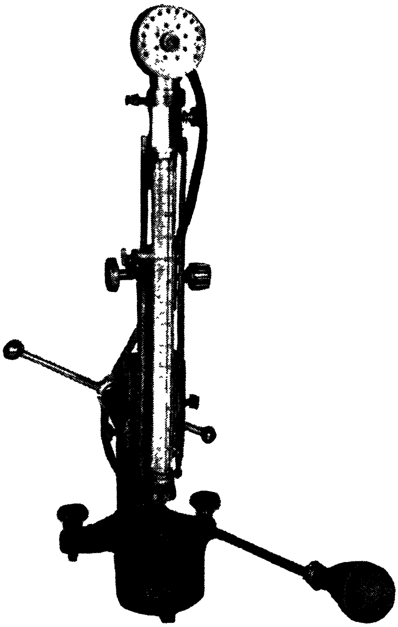


FIG. 77. Shore Scleroscope for measuring hardness by height of rebound of diamond tipped hammer. Direct reading type. Instrument made by The Shore Instrument and Manufacturing Company.

move the specimen to complete the test. To prevent damage to the diamond point due to striking super-hard metal do not allow the hammer to strike more than once on the same spot.

To speed up the cycle of operation and to eliminate the difficulty of determining the rebound height by eye the Shore Scleroscope has been remodeled and fitted with a self-indicating dial as shown in Figure 78. In this instrument the weight is projected against the test surface by tripping a spring. The cycle of testing is carried out with the one control handle.

The Scleroscope hardness tester is particularly applicable to proof testing of finished parts as it leaves no visible surface marks. On either the direct reading or self-indicating types of Shore instruments the test head may be removed and used by holding it over the work. This method offers an advantage when the work to be tested is too large to be placed in the machine itself.

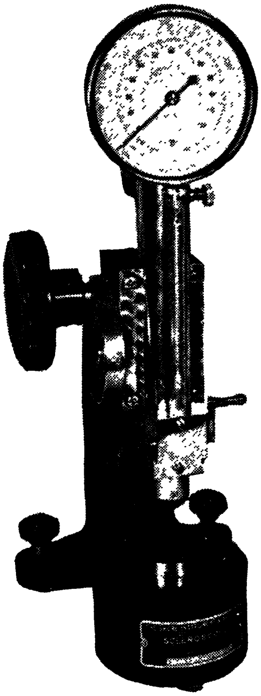


FIG. 78. Self-indicating type of Shore Scleroscope hardness tester, manufactured by The Shore Instrument and Manufacturing Company.

VICKERS, FIRTH, AND MONOTRON HARDNESS TESTS—Among the many other hardness tests available but not discussed here are the following which are more commonly used:

Vickers. A machine used extensively in England and by research workers in this country. It is a penetration type of test in which the impression left by a 136° diamond pyramid is measured for loads varying from 1 to 120 kg. The apparatus is motor driven for speed and constancy of testing. A distinct advantage of this method is the fact that the contact area can more accurately be obtained from the diagonal of the square impression than by the method of measuring tangents (and thus diameter and area), as is done in the Brinell test.

Firth. The Firth Hardometer is another English machine similar to the Vickers and actually uses the Vickers instrument. Loads of 10, 30, and 120 kg. are applied by springs to 1, 2, or 4 mm. steel balls or to the 136° diamond pyramid. Usually the impression is magnified and projected onto a graduated screen for ease of reading.

Monotron. Another indentation hardness tester in which a measurement is made of the load required to produce an arbitrary penetration of 0.045 mm. for a 0.75-mm. hemispherical diamond indentor. The load is measured in kilograms per square millimeter. Since the depth measurement is made with respect to the original surface and while the indentor

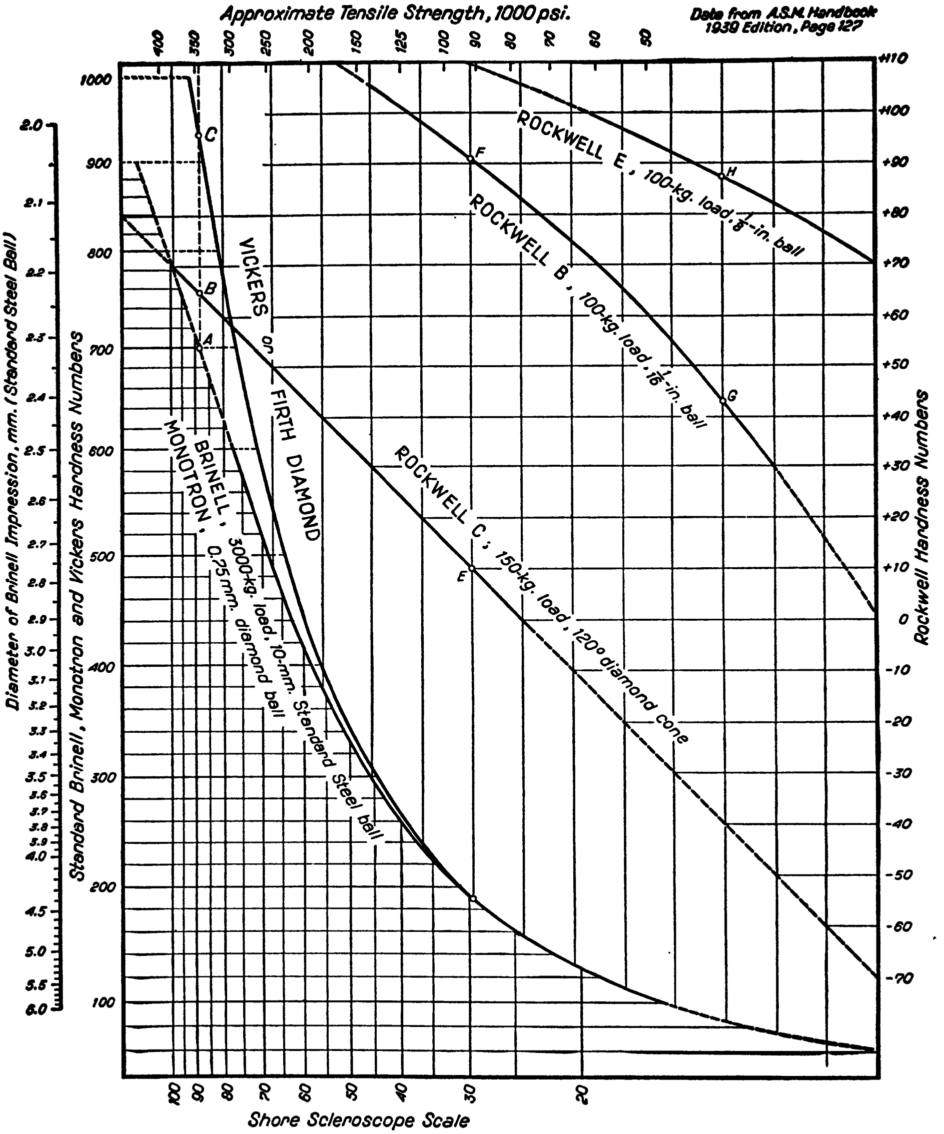


FIG. 79. Hardness conversion chart for steels.

Verticals represent equivalent hardness.

For instance: Brinell or Monotron 700 (point *A*) equals Rockwell C-65 (point *B*), equals Vickers 930 (point *C*), equals Scleroscope 89 (*bottom scale as modified by data from Westinghouse Research Laboratories*), and about 340,000 psi. tensile (*top scale*).

Again: Rockwell B-91 (point *F*) equals C-10 (point *E*), equals Brinell, Monotron or Vickers 187 and Scleroscope 29, and has about 92,000 psi. tensile strength.

Finally, Rockwell B-43 (point *G*) equals E-87 (point *H*). Curve for latter scale is from Bureau of Standards Research Paper No. 185. (Courtesy American Society for Metals) is under load, the edge conditions shown in Figure 74(b) have no influence on the result.

Although it has been impossible to correlate the results of all hardness test methods for all types of materials, it has been done for steels. A correlation or hardness conversion chart of this type is shown in Figure 79.

PREPARATION OF REPORT

COMPARISON CHART

On a chart similar to the sample show the relation of the results of the various hardness test methods. This may be done by taking the Brinell hardness as a basis for comparison and using the scale given on the chart. Opposite the Brinell hardness of each specimen make a mark on the Rockwell or Scleroscope line and write the observed hardness value adjacent to this mark. When all of the specimens have thus been shown on the chart, the values marked for Rockwell and Scleroscope should increase uniformly as the Brinell numbers increase.

The relationships between Brinell and Rockwell hardness numbers have been given by Petrenko in Technological Paper No. 334, a publication of the National Bureau of Standards, as follows:

$$\text{B.H.N.} = \frac{7300}{130 - R_B} \quad \text{for Rockwell B greater than 35 and less than 100}$$

$$\text{B.H.N.} = \frac{1{,}420{,}000}{(100 - R_C)^2} \quad \text{for Rockwell C greater than 20 and less than 40}$$

$$\text{B.H.N.} = \frac{25{,}000}{100 - R_C} \quad \text{for Rockwell C greater than 40}$$

COMPUTATIONS

Compute the Brinell hardness number of at least one specimen, using the formula previously given.

Compute the Brinell hardness values of three materials from their Rockwell hardness values, using the relationships given above. Select one material that may be used for each of the formulas. Use a computation form similar to the following:

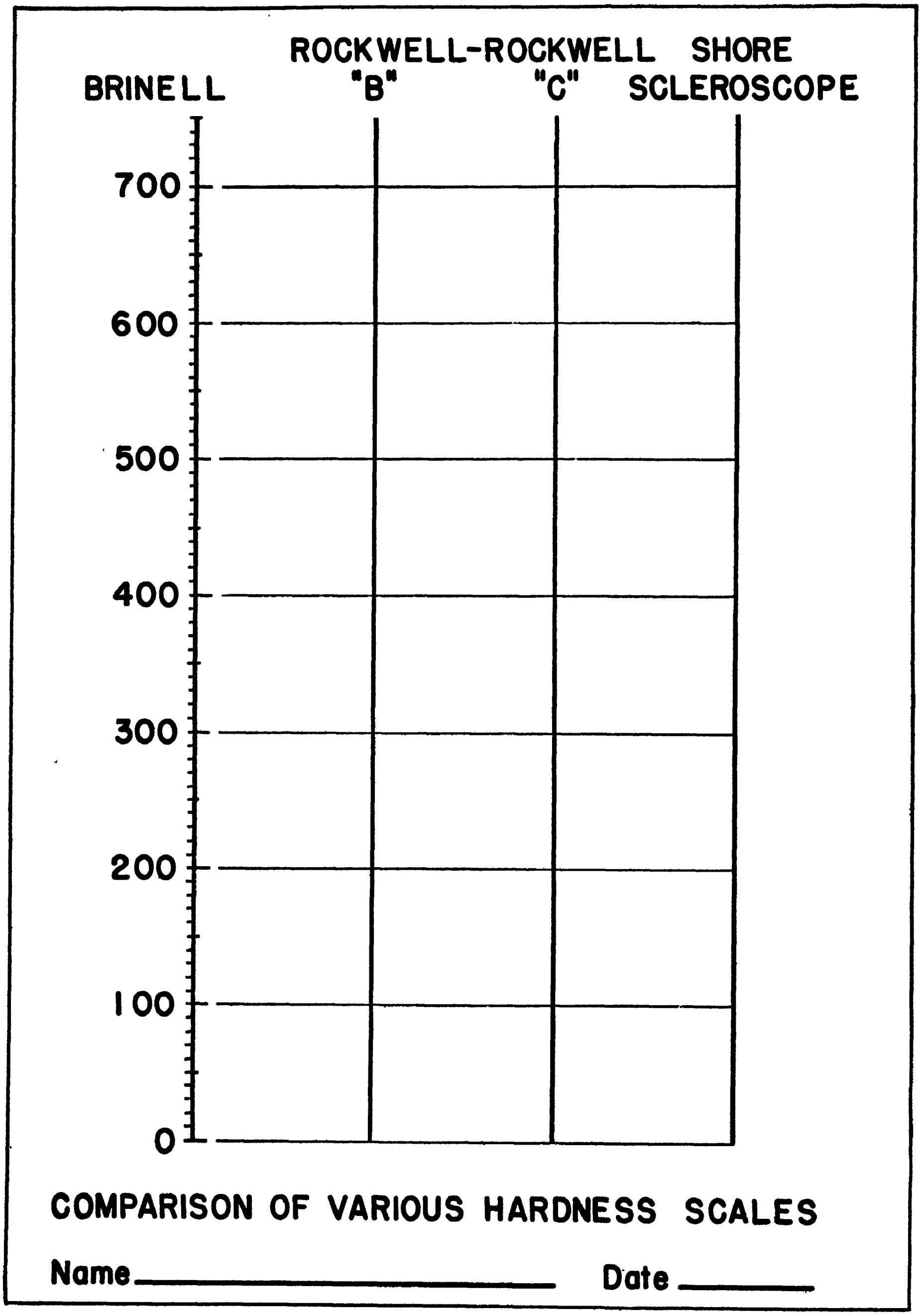
Material ....
Rockwell Hardness = ... Computed B.H.N. = ...
Actual measured B.H.N. = ... Error = ... per cent

DISCUSSION

1. It is possible to correlate the hardness of a material and its tensile strength. The error of most conversion formulas for strength is from 10 to 15 per cent, plus or minus. The best relationships have been given for steel in the National Bureau of Standards publication previously referred to. They are as follows:

$$s_t = 515\ (\text{B.H.N.}) \quad \text{for B.H.N. less than 175}$$

$$s_t = 490\ (\text{B.H.N.}) \quad \text{for B.H.N. greater than 175}$$



Manner of comparing various hardness scales, Experiment 11.

$$s_t = \frac{3.75(10^6)}{130 - R_B}$$ for Rockwell B less than 90

$$s_t = \frac{3.57(10^6)}{130 - R_B}$$ for Rockwell B greater than 90 and less than 100

$$s_t = \frac{730(10^6)}{(100 - R_C)^2}$$ for Rockwell C less than 10

$$s_t = \frac{695(10^6)}{(100 - R_C)^2}$$ for Rockwell C greater than 10 and less than 40

$$s_t = \frac{12.25(10^6)}{100 - R_C}$$ for Rockwell C greater than 40

These relationships are not applicable to aluminum or other non-ferrous metals.

Fill in the following table comparing hardness and computed and actual tensile strengths for representative materials, using tensile strength values previously obtained or furnished by the instructor and account for the variation in actual and computed tensile strengths when the error is more than 10 per cent:

Material	Brinell hardness	Rockwell hardness	Computed tensile strength	Actual tensile strength	Error, per cent

2. Which of the hardness methods studied would be most affected by surface scale, pits, scratches, or other imperfections? Why?
   Which method would be affected the least? Why?
3. If a material is too thin to be used in a hardness test of any type, would it be satisfactory to use several layers in making the test? Why?
4. Account for any gross lack of consistency found in the comparison chart previously plotted.
5. All important factors considered, which test would be most applicable to a wide variety of materials covering the range from very soft to very hard? Why?

EXPERIMENT 12

THE PHYSICAL PROPERTIES OF CONCRETE

Concrete and its products are primarily materials of the civil, structural, or architectural engineer and are used by electrical and mechanical engineers only in minor capacities, such as foundations, machine bases, etc. Many tests of the cement, aggregates, and even the water used in making concrete, are necessary for control of quality and uniformity. These tests are not considered a part of the general course in the Materials Laboratory but should be included as supplementary information for those interested. This experiment is intended to acquaint the student with the most important factors which influence the making of concrete and affect the physical properties of both the fresh and hardened product.

Cement, used as the adhesive which binds the aggregate together, is made of approximately 60 per cent lime-bearing material, such as limestone, and 40 per cent of a clayey material, such as shale or blast-furnace slag. These are ground, mixed together, and then heated to about 2800° F., at which temperature they fuse. This product, when ground fine and mixed with about 3 per cent gypsum (calcium sulfate) to retard the hardening time, is standard Portland cement. When mixed with water and allowed to set it forms a rigid product which subsequently cannot be made to soften again when wet. A sack of cement contains 1 cu. ft. of material and weighs 94 lb. It is ground so fine that 85 to 90 per cent of it will pass through a sieve containing more than 100,000 openings per square inch. High early strength cement differs from ordinary cement only in that it is ground more finely.

The concrete made with cement and aggregates, such as sand and gravel, has physical properties and characteristics which are dependent upon the properties of those materials. All of these ingredients are made up of angular particles which cannot be packed together so tightly as to produce a voidless volume. The void spaces must be filled with a finer material until no appreciable void space remains. The structure of the concrete may be analyzed as follows:

Cement

The cement is only about 50 per cent solid material so the void space in it must be filled with voidless water. Therefore, *Cement + Water = Voidless Paste*

Sand

The sand is only about 65 per cent solid material, so the void space in it must be filled with voidless paste. This cements the sand grains together and forms *Sand + Voidless Paste = Voidless Mortar*

Gravel

The gravel is only about 65 per cent solid material, so the void space in it must be filled with voidless mortar. This binds the stones together and forms *Gravel + Voidless Mortar = Voidless Fresh Concrete*

Actually, air is entrapped in the concrete during mixing so that the fresh concrete is not voidless. As the concrete sets and cures, the water in the fresh concrete that does not actually combine chemically with the cement to cause setting (only about 20 per cent is needed for this) is left to evaporate slowly. This evaporation produces voids in the concrete. It may be seen, therefore, that the quantity of water used in making the concrete has considerable effect on its final density, and also on other properties, as will be shown.

To complete the setting action of the cement three things are necessary, as follows:

1. Time: initial set in several hours, final strength in several days or weeks depending on factors to be shown.
2. Favorable temperature: generally between 50° F. and 90° F.
3. Curing water: to complete the setting action rapidly and to provide quick curing it is necessary to keep the concrete well supplied with curing water.

The sand and gravel used in a concrete mixture should be well proportioned or graded from fine to large particles. Sands generally vary in particle size from ¼ in. down to those which will pass a 100-mesh sieve (10,000 openings per sq. in.). Gravels vary upward from ¼ in. to 1.5 in. and often to 2.5 in. If the sand or gravel is well graded within itself the void space will be at a minimum and consequently less paste is needed to produce concrete. The workability of the fresh concrete is also improved, yielding a better finished surface. Figures 80(a) and (b) illustrate samples of well graded and poorly graded aggregates. All aggregate used in concrete must be sound and free from soft particles. The shape of the aggregate has no effect upon the strength of the concrete. Concrete mix proportions may be on the basis of volume or weight and are stated as a

1-2.5-3.5 mix by volume,

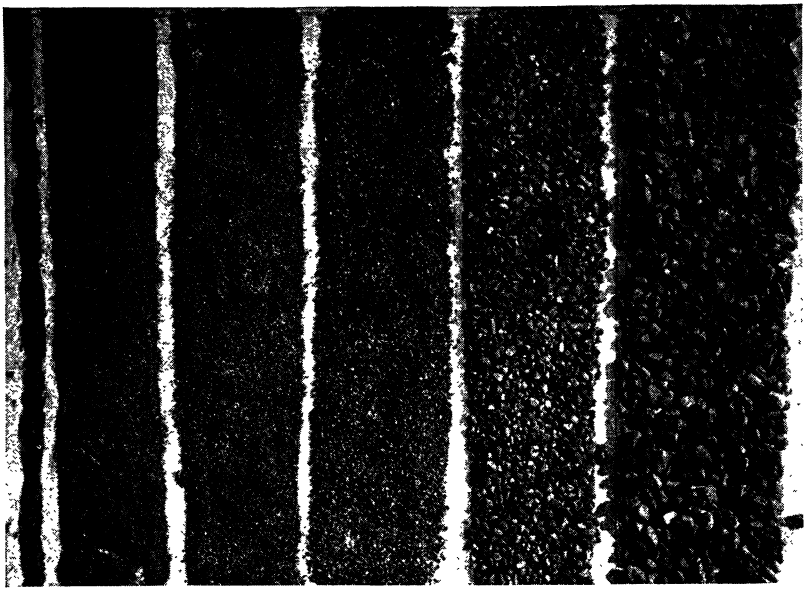


FIG. 80(a). Sample of well graded sand before and after it has been separated in various sizes. Particles vary from fine up to ¼ in. in size. This is good sand for concrete work. For good workability, at least 5 per cent should pass a 50-mesh sieve. (Courtesy Portland Cement Association)

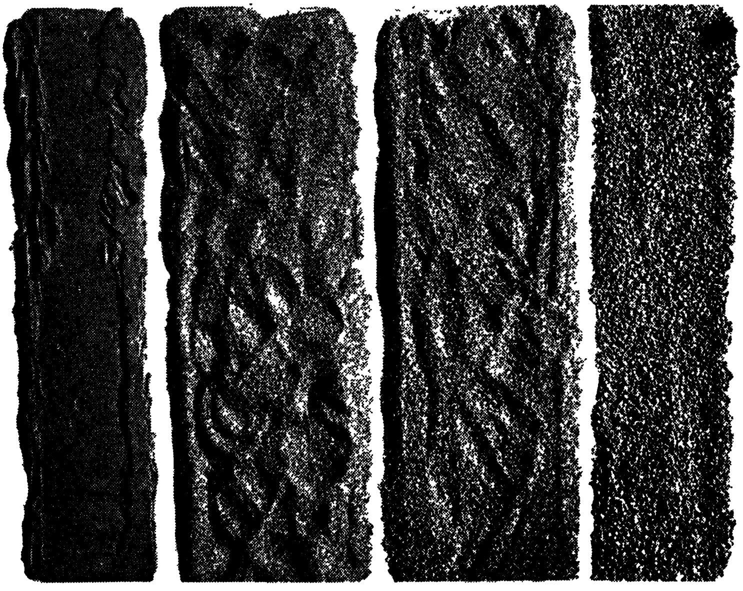


FIG. 80(b). Sample of poorly graded sand which lacks particles coarser than $\frac{1}{16}$ in. in size, showing how it looks when separated into four sizes. Ordinarily such a sand is not as economical as sand of coarser grading. (Courtesy Portland Cement Association) meaning that 1 part of cement, 2.5 parts of sand, and 3.5 parts of gravel, all by volume, should constitute the mix.

The most important single variable governing all the properties of concrete is the quantity of water used in its mixing. This fact was shown by D. A. Abrams in 1918 and led to the engineer's present ability to design and control the quality of concrete and thus make of it a dependable structural material. Abrams' water-cement ratio law, as this relationship is called, may be stated as follows for sound, durable aggregate and sound cement:

> All the desirable properties of concrete are
> lowered with an increase in the quantity
> of mixing water (water-cement ratio).

The desirable properties of concrete include primarily

1. Strength: concrete is always used in compression.
2. Durability: resistance to freezing and thawing.
3. Wearability: ability to resist abrasion.
4. Water tightness: lack of permeability.

The only property of concrete that is affected by an increase in water-cement ratio is the workability or placability of the fresh concrete. The properties previously given are those of the final usable concrete as visualized by the designer, whereas the workability is a property which determines the ease and speed with which the builder is able to place the fresh concrete. It is apparent that if one factor increases, the other must decrease. It is necessary, therefore, that the student be able to realize the limiting boundaries for each viewpoint and provide for a concrete mix that will have the desired final properties and yet be workable and placable in the field.

The water-cement ratio is usually expressed as gallons of water per sack of cement. Occasionally it is expressed as cubic feet of water per cubic foot of cement. Some characteristic relationships between compressive strength and water-cement ratio are given on the sample sheet of cross-section paper shown. Notice that the high early strength cement produces a concrete which at 3 days has the strength of the ordinary cement at 28 days. The relationship expressed by this curve holds for any proportions of mix, within reasonable limits; therefore, the relative proportions of sand plus gravel to cement have practically no effect upon strength.* It does, however, affect the other properties mentioned, causing a general decrease in durability and wearability and an increase in permeability. The best ratio of sand to sand plus gravel is about 0.60 for a ⅜-in. maximum size of aggregate, 0.50 for a ¾-in. maximum, and 0.40 for aggregate larger than 1 in. These ratios may be varied depending on the properties of the materials. The relative total proportion of sand plus gravel to cement will vary depending on the following:

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* Provided that enough additional mixing water is added to surface moisten the aggregates.

1. The durability required as based on previous experience or actual tests.
2. The cost of the mix consistent with the properties desired.
3. The water-cement ratio used for strength.
4. The workability required for placing.

It can be seen that, if the proportions of sand plus gravel to cement are increased, the water-cement ratio must also be increased to provide the same workability. For average workability and sizes of aggregate the following proportions * will serve as a guide:

Water-cement ratio, gallons per sack	Mix proportions by volume		
	Cement	Sand	Gravel
5.5	1	1.75	2.5
6.0	1	2	3
6.75	1	2.25	3.25
7.5	1	2.50	3.75

If decreased workability can be permitted the amount of sand and gravel can be increased slightly (about 0.30). If increased workability is required the amount of sand and gravel must be decreased (also about 0.30). For a gravel of 2-in. maximum size, rather than the 1-in. maximum for which the above table is given, the volume of gravel may be increased by about 15 to 20 per cent. In Table I, p. 149, are given various water-cement ratios to be used for various conditions of exposure.

This experiment may be carried out in one of two ways. If time permits, the class may mix the concrete using the proportions assigned to them by the instructor, mold the test specimens, and test them after the required curing time. If time is not available actually to mix the concrete, the specimens may be prepared beforehand and the class will then perform the experiment for strength only. In this latter case the instructor will provide each squad with the information which would otherwise have been obtained while mixing.

EXPERIMENTAL PROCEDURE

APPARATUS—For mixing—mixing board, shovels, trowel, slump cone, 12-in. scale, tamping rod, and steel cylinder molds 6 by 12 in. For testing—Uni-

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* Summarized from "Design and Control of Concrete Mixtures," 1940, a publication of the Portland Cement Association.

EXPERIMENT 12

THE PHYSICAL PROPERTIES OF CONCRETE

Cement Brand ______________ Maximum Coarse Aggregate Size ____________ Type of Coarse Aggregate ______________

Name ______________________________ Date ____________________ Squad Members ______________

FRESH CONCRETE									(SET) CONCRETE CYLINDERS									
Squad	Mix by volume			Weights of material used in mix			Slump, in.	Water-cement ratio	Dimensions			Weight, lb.	Unit weight, lb/cu ft	Type of failure	Maximum load, lb.	Compressive strength, psi.	Average compressive strength, psi.
	Cement	Sand	Coarse A.	Cement	Sand	Coarse A.			Diameter	Area	Length						

Sample data sheet for Experiment 12.

versal testing machine, spherical bearing block, calipers, 12-in. scale, and compressometer for concrete (if required).

MATERIAL—Standard grade of Portland cement, well-graded sand, and well-graded gravel of 1.5-in. maximum size.

Each squad will be assigned a different water-cement ratio or mix proportion, or both. The data obtained by each squad will then be assembled on a data sheet similar to the sample shown.

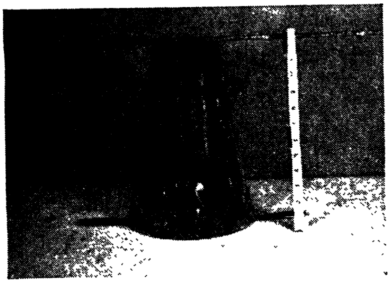


FIG. 81. Slump cone, straight edge and ruler for measuring consistency of fresh concrete.

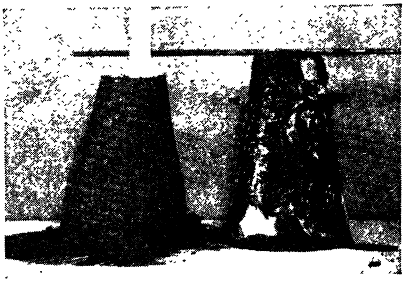


FIG. 82. Two-inch slump of stiff concrete mix.

Mix the materials assigned by first combining the sand and cement, then adding the gravel, and finally the water. The consistency (a measure of the workability) may be measured with the slump cone apparatus shown in Figure 81. The mold is a truncated cone conforming to A.S.T.M. Designation C143-39, or later. To make the slump test, fill the mold one-third full of fresh concrete and rod 25 times with the tamping rod provided. Repeat this procedure two more times until the mold is full, rodding each time with 25 strokes that penetrate into the previous layer. Carefully strike off the top, raise the mold, and measure the slump. Some representative slumps for stiff, medium, and wet mixes are shown in Figures 82, 83, and 84, respectively. The slump test is a good field test for consistency and may actually be used to govern the amount of mixing water.

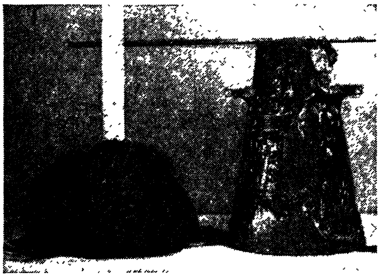


FIG. 83. Six-inch slump of normal concrete mix.

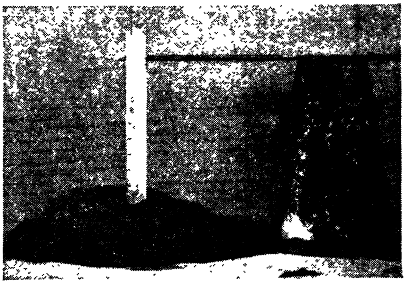


FIG. 84. Ten-inch slump of wet concrete mix.

The compression test cylinder should be 6 in. in diameter and 12 in. high, conforming to A.S.T.M. Designation C39-39, or later. Fresh concrete should be placed in the mold in three layers and by rodding as for the slump test. It is desirable that three test specimens be made by each squad. The cylinder molds will be stripped after about a 48-hr. curing time and the specimens will then be stored in the curing room at the temperature and humidity designated by the instructor.

Before testing the compression cylinders they must be capped on the end to permit uniform bearing when the load is applied. The cap may be made of plaster of Paris, neat cement, or lead. It should not be so thick as to fail itself or so thin as to chip off. Load should be applied to the specimen through a spherical bearing block.

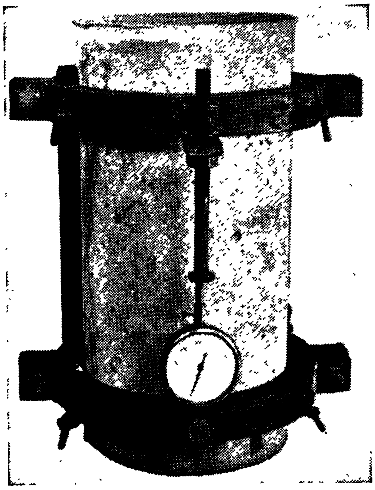


Fig. 85. Compressometer attached to concrete test cylinder.

Weigh each cylinder and obtain its length and average diameter to the nearest 0.01 in. Calculate the unit weight and record on the data sheet. If the stress-strain diagram is to be obtained for the concrete in compression, it will be necessary to use a compressometer of the type shown in Figure 85, an 8-in. gage length instrument being preferred. When this data is to be obtained, the student should make out a suitable data sheet on which to record loads and deformations. A typical compressive stress-strain diagram for an average concrete is shown in Figure 86. Note that the diagram shows no straight-line relationship of stress to strain. In order to find the modulus of elasticity of concrete it is necessary to draw a tangent to the diagram at some arbitrary value of stress and thus determine the tangent modulus as shown in Figure 86. Another elastic modulus value often used for concrete is the *secant* modulus of elasticity. To find this value a straight line is drawn from the origin to the arbitrary stress and the slope of this line is taken as the secant modulus of elasticity.

The value obtained for the secant modulus is not the true modulus at the stress selected but is somewhat higher. Actually it approximately averages the initial modulus (high) and the tangent modulus for all stresses between zero and that selected. It should be observed from the compressive stress-strain diagram in Figure 86 that concrete, even when subjected to normal working loads, may exhibit permanent set upon release of load.

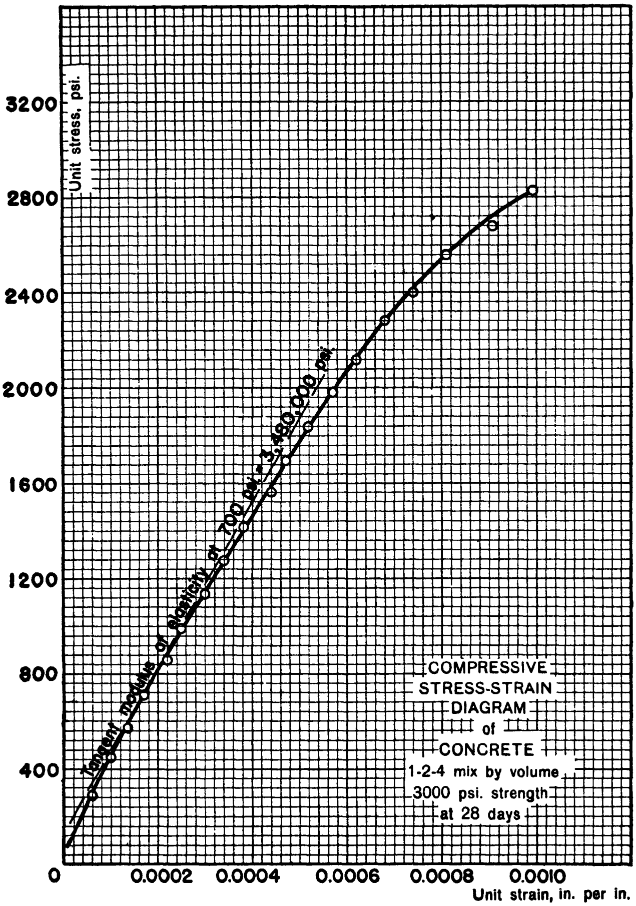


FIG. 86. Compressive stress-strain diagram of a 1-2-4 concrete mix showing tangent modulus at 700 psi. Note also the manner of plotting data and showing scales on coordinate axes.

Load the specimen to fracture and observe the ultimate load. Concrete fails with a shear type of break in one of two ways.

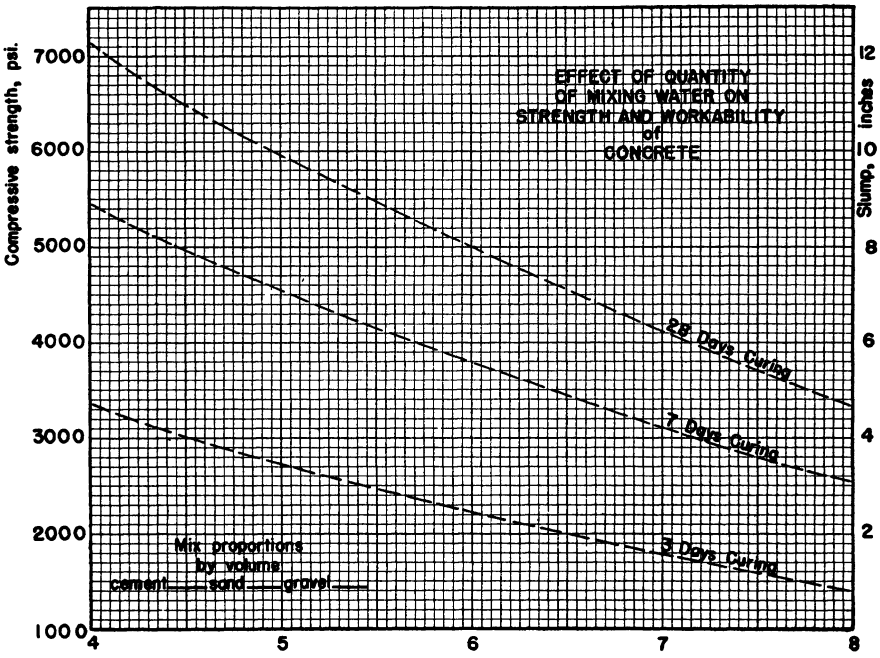
1. Bond failure: the tenacity of the bond of the mortar was not sufficient to knit the coarse aggregate together.
2. Aggregate failure: the bond was stronger than the aggregate, causing failure through the latter. This is the type of failure most indicative of strong, high quality concrete.

Record and summarize all test results for the squad on the data sheet and secure the same information from other squads for their individual mixes.

Preparation of Report

COMPUTATIONS

All computations employed in reducing the data are minor and therefore only test results need be shown on the data sheet.



Data from Portland Cement Association, "Design and Control of Concrete Mixtures"

Sample sheet of cross-section paper for water-cement ratio curve in Experiment 12, showing coordinate scales. Curves for average compressive strength at 3, 7, and 28 days to be transferred to final graph sheet and thus compared with experimental data.

From the stress-strain diagram obtained for concrete, or from that provided with this experiment, calculate the modulus of resilience of the material at a stress of .... psi. and compare it with the steel tested in Experiment 2.

E'_R for concrete..........

E_R for steel (Exp. 2)..........

$$\text{Ratio } \frac{E'_R \text{ for concrete}}{E_R \text{ for steel}} = \dots\dots\dots\dots$$

WATER-CEMENT RATIO CURVE

The sample cross-section paper shown has the Portland Cement Association average strength curves plotted on it. The data for both compressive strength and slump should be plotted against water-cement ratio on this sheet. Draw a smooth curve through the plotted points and label this curve "test curve, ... days."

DISCUSSION

1. Do the results of the test prove the validity of Abrams' water-cement ratio law?
2. Account for any great discrepancy between the "test curve, ... days" and the Portland Cement Association curve for the same curing time.
3. Assume that a concrete structure is to be made of a concrete having the same strength as that obtained for the assigned mix but that this strength must be attained in 3 days. Using ordinary Portland cement, approximately what would the water-cement ratio be? Using high early strength cement, approximately what would the water-cement ratio be? Would it be necessary to reduce the proportions of aggregate in either case to provide approximately the same workability? If so, what would the final proportions be?
4. In the introduction to this experiment it was stated, "The best ratio of sand to sand plus gravel is about 0.60 for a 3/8-in. maximum size of aggregate, 0.50 for a 3/4-in. maximum, and 0.40 for aggregate larger than 1 in." It may be seen from this statement that a pea-sized gravel will require more sand for a workability comparable to that of a 1.5-in. gravel. Keeping in mind the analysis of the concrete mixture previously made, why must this be true?

TABLE I. WATER CONTENTS SUITABLE FOR VARIOUS CONDITIONS OF EXPOSURE (GAL. PER SACK OF CEMENT)

This table is reprinted from the Report of the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete †

Type of Location of Structure	Severe or Moderate Climate, Wide Range of Temperatures, Rain and Long Freezing Spells, or Frequent Freezing and Thawing					Mild Climate, Rain or Semi-Arid, Rarely Snow or Frost				
	Thin sections		Moderate sections		Heavy and mass sections	Thin sections		Moderate sections		Heavy and mass sections
	Reinf.	Plain	Reinf.	Plain		Reinf.	Plain	Reinf.	Plain	
A. At the waterline in hydraulic or waterfront structures or portions of such structures where complete saturation or intermittent saturation is possible, but not where the structure is continuously submerged:										
In sea water	5	5½		6		5	5½		6	
In fresh water	5½	6		6½		5½	6		6½	
B. Portions of hydraulic or waterfront structures some distance from the waterline, but subject to frequent wetting:										
By sea water	5½	6		6		5½	6½		7	
By fresh water	6	6½		6½		6	7		7½	
C. Ordinary exposed structures, buildings and portions of bridges not coming under above groups	6	6½		7		6	7		7½	
D. Complete continuous submergence:										
In sea water	6	6½		7		6	6½		7	
In fresh water	6½	7		7½		6½	7		7½	
E. Concrete deposited through water	*	*	5½	5½		*	*	5½	5½	
F. Pavement slabs directly on ground:										
Wearing slabs	5½	6	*	*		6	6½	*	*	
Base slabs	6½	7	*	*		7	7½	*	*	

G. Special cases: (a) For concrete exposed to strong sulfate ground waters, or other corrosive liquids or salts, the maximum water content should not exceed 5 gal. per sack.

(b) For concrete not exposed to the weather, such as the interior of buildings and portions of structures entirely below ground, no exposure hazard is involved and the water content should be selected on the basis of the strength and workability requirements.

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* These sections not practicable for the purpose indicated.

† "Recommended Practice and Standard Specifications for Concrete and Reinforced Concrete," 1940, a Joint Committee Report of the American Society of Civil Engineers, American Society for Testing Materials, American Railway Engineers Association, American Concrete Institute, and Portland Cement Association.

EXPERIMENT 13

COLUMN TESTS

An engineering material may fail in compression by elastic buckling, plastic distortion, or actual rupture, depending on the size of the part and the properties of the material. It has already been shown that for short compression members ductile materials fail by plastic distortion (steel in Experiment 4) and brittle materials fail by actual rupture (cast iron in Experiment 8, concrete in Experiment 12, and plastics in Experiment 10). Yet to be investigated is the failure of long narrow columns of either type of material.

A compression member may be considered to be a column when the length of the member is more than 10 times the least lateral dimension. When a column is loaded two sets of stresses are set up. One of these is due only to the direct compression and may be determined from $s = P/A$. The other stress is due to bending of the column, as a beam but due to axial end loads, and may be obtained from the flexure formula $s = Mc/I$. The value of M in this latter formula is dependent upon the amount the column deflects laterally from its original position. To prevent elastic buckling it is necessary that the bending be very small or non-existent. The maximum load which a column can resist without bending (buckling) may be found from mechanics as

$$P = \frac{\pi^2 EI}{L^2}$$

in which P = load applied to column, lb.

E and I as for beams (see Experiment 5).

L = length of column, in.

When I in this relationship is expressed in terms of the area and radius of gyration of the cross section the formula may be written

$$\frac{P}{A} = \frac{\pi^2 E}{(L/r)^2}$$

in which A = cross-sectional area of column.

r = radius of gyration of the cross-section. This term is defined as the distance from a line at which the area may be considered concentrated and yet have the same moment of inertia about that line as the actual distributed area. Some representative values are

Rectangular section: $r = \dfrac{\text{least side}}{3.46}$

Solid circular section: $r = \dfrac{\text{diameter}}{4}$

Tube of outside diameter, d_O, and inside diameter, d_I: $r = \dfrac{d_O + d_I}{5.64}$

L/r = the slenderness ratio of the column, a very useful term in considering column action and the possibility of failure due to buckling.

This is the Euler column formula. It is shown in Figure 87 in its theoretical form. When the unit stress, s, reaches P/A the column will fail in direct axial compression rather than by buckling, as shown by the dotted line in Figure 87. Other column formulas are available in any strength of materials text and may be compared with the Euler formula by the student.

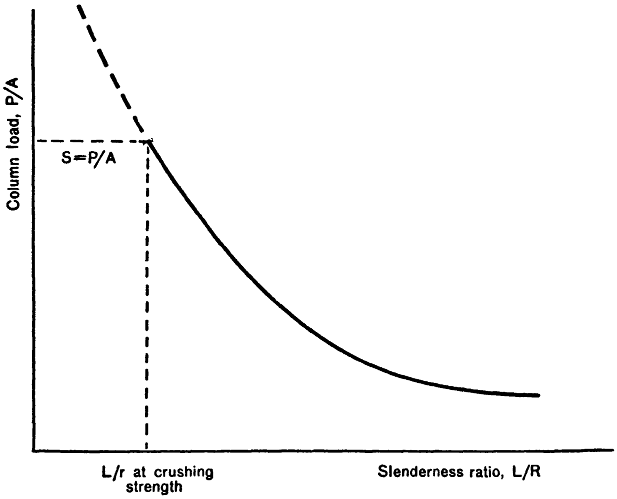


FIG. 87. Graph of Euler column formula.

The analysis previously presented is for ideally straight columns free to rotate at the ends (pin-ended). Although the matter will not be discussed in detail here, it should be pointed out that end conditions have considerable effect on the maximum load which a column will support before buckling. The pin-ended column has the least end restraint, while a column fixed against rotation at each end has the greatest end restraint. Other conditions include one end fixed and the other end pin-ended, or one end fixed and the other end unsupported. In actual structural or mechanical design none of these assumed conditions ever exist, due to the details of fastening members together by riveting, welding, and bolting.

This experiment is intended to illustrate the importance of slenderness ratio on column action and to show the manner and extent of failure as this ratio is varied over a wide range.

EXPERIMENTAL PROCEDURE

APPARATUS—Universal testing machine having sufficient clearance between crossheads to test a column 40 to 48 in. long, pin-ended bearing plates, 12-in. scale, and calipers.

MATERIAL—It is preferable that wood be used for the column material (if a metal column is tested it is advisable that it be a material having a low modulus of elasticity). Wood permits a larger cross section, since E is smaller, and thus provides a specimen that is more quickly centered in the machine. The cross section should be symmetrical. The cross section of a wood column may vary from 1.5 to 2.0 in. square or rectangular, and the length from 40 to 48 in. It is desirable that the length and least dimension of the cross section be selected so that a maximum slenderness ratio of about 150 is obtained.

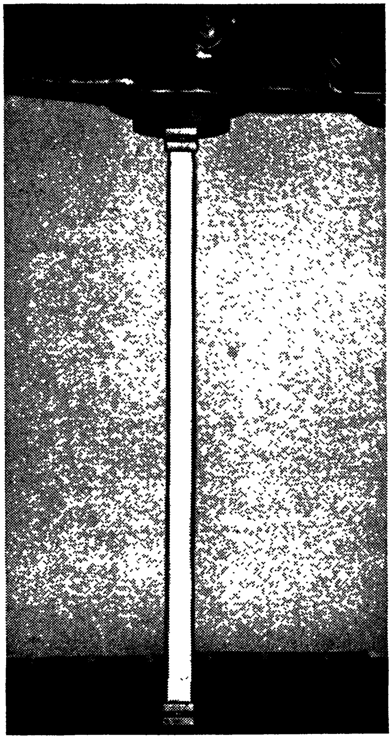


FIG. 88. Long slender column set up ready for test. Note spherical bearing blocks at ends. Slenderness ratio of this specimen is 100.

A column set up in the testing machine ready for test is shown in Figure 88. The details of the spherical bearing blocks, which simulate a pin-ended condition, are shown in the close-up of Figure 89. The column should be placed on these bearing blocks and carefully centered. Measure the dimensions of the cross section at several places along the length and to the nearest 0.01 in. All specimens will be cut to an even value of length. For convenience the measurements may be taken with the specimen in place in the testing machine and with a small load applied.

Test the longest column first. When the dimensions have been obtained, increase the load slowly until the column buckles elastically. Note this load and then release it until the column is again free. Move it slightly toward the side that buckled by shifting both the top and bottom spherical seats in that direction. Again reload the column and obtain the buckling load. If this load is not higher than the previous value take the higher of the two as the column load. If the second load is higher than the first, the specimen originally was not properly centered in the machine. Repeat this procedure until the maximum buckling load is obtained for each column. Some of the specimens of low slenderness ratio will fail by crushing rather than by buckling. These columns are theoretically at the point $s = P/A$. On the data sheet, therefore, state the manner in which each specimen failed.

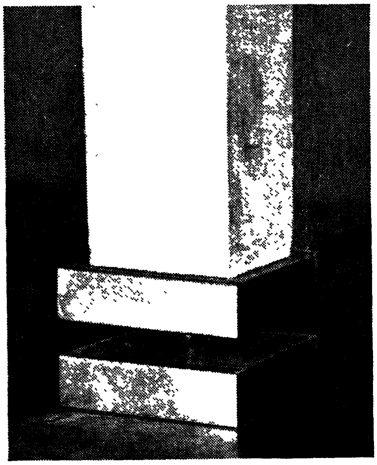


Fig. 89. Close-up of spherical bearing block designed to simulate pin-ended condition in column. Steel ball 10 mm. in diameter may be seen between end plates.

After a column buckles it may be reduced in length and retested until too short to fail by column action.

Preparation of Report

COMPUTATIONS

Space should be provided on the data sheet for the results of all computations necessary to present the data.

EXPERIMENT 13

COLUMN TESTS

Material

Name Date

Specimen	Length, in.	Dimensions of cross section, in.	Radius of gyration, in.	L/r	$(L/r)^2$	Theoretical column load $\frac{P}{A}=\frac{\pi^2 E}{(L/r)^2}$	Load * on specimen, lb.	Actual column load, P/A

Modulus of elasticity =

$\pi^2 E =$

* If specimen fails by crushing, place a C after the load, if by buckling, place a B after the load.

Sample data sheet for Experiment 13.

COLUMN CURVE

On cross-section paper similar to the sample shown plot the relationship of column load, P/A, to slenderness ratio. Draw a smooth solid curve that averages these points, including those where column failure occurred by crushing rather than by buckling. On the same graph sheet plot the relationship of theoretical column load, from the Euler or any other formula, for the slenderness ratios used. If the same wood is used for columns as was used for the beam in Experiment 5 the value for modulus of elasticity may be taken as found for bending. Otherwise use the value of E given by the instructor. The theoretical curve should be plotted as a dotted line.

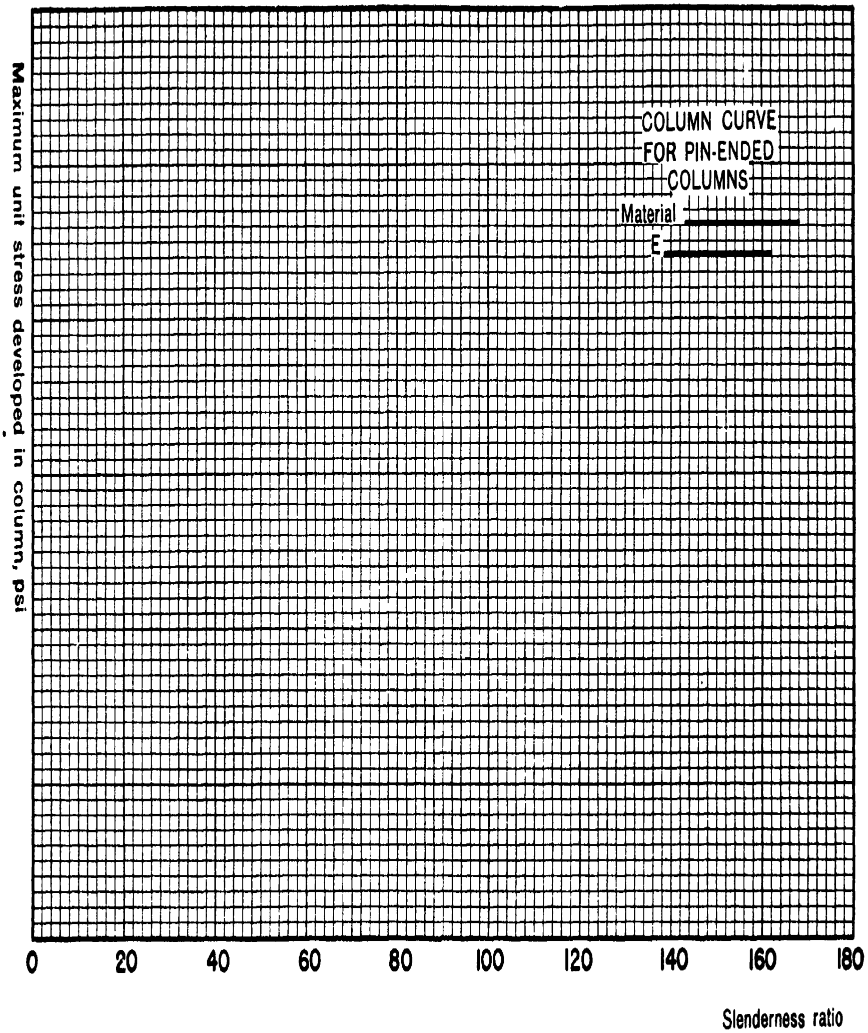
DISCUSSION

1. Do the theoretical and actual values of column load agree? Account for any discrepancy.
2. What property of a material governs its strength as a column?
3. As shown in the introduction to the experiment, the stress in a column is due to axial load and bending so that

$$s = \frac{P}{A} \pm \frac{Mc}{I}$$

(The plus or minus sign is necessary since the axial and bending stresses are opposed on one side of the column and combined on the other.) Of the specimens tested in this experiment, which might be analyzed safely using only the first term of this relationship? Which, when the second term only is used? Why?

4. How could the modulus of elasticity of a material be determined from the column test?
5. For this material, what maximum slenderness ratio can be used without failure by column action?



Sample sheet of cross-section paper for column curve in Experiment 13, showing coordinate scale for slenderness ratio. Scale for column stress to be filled in.

EXPERIMENT 14

STRAIN GAGES AND THEIR USE

The fundamental relationships of Hooke's law and the modulus of elasticity give the materials testing engineer one of his most valuable tools. When written as in Equation (7)

$$E = \frac{s}{\epsilon}$$

it can be seen that any one quantity may be found if the other two are known. Since the modulus of elasticity of any material may be determined by independent tests it is necessary only to measure the strain existing in a test specimen to determine the magnitude of the stress or unit load. Strain gages used for this purpose may be small enough to weigh less than an ounce and yet measure a change of length of two millionths of an inch. They are attached by clamps, suction cups, rubber bands, weights, or glue and may be placed in locations inaccessible to other types of equipment. Their use in the determination of unit stresses permits the designer to decide if a mechanical or structural part is safely designed. The use of strain gages has led to the intelligent redesign of structures, machine parts, and the modern streamlined train, trucks, and busses, as well as many interesting applications in the development of aircraft.

Strain gages are divided into three types as follows:

1. Mechanical
    - *a.* Direct reading
    - *b.* Magnified reading
2. Electrical
3. Optical

All types of gages will be discussed briefly here. The principal purpose of the experiment is to acquaint the student with the manner of use and the subsequent application of any type of gage. In general, the actual use of any one type of gage is a matter of technique and does not necessarily require a knowledge of the principles involved.

A direct reading strain gage that permits the measurement of distance between two points without magnification is shown in Figure 90. This Whittemore gage employs plate fulcra that bend elastically in the direction of the gage length and thus yield a direct measurement of strain. The dial reads directly to 0.0001 in. and by estimation to one tenth of this amount. The Whittemore gage, because it does not magnify the strain, gives good duplication of results and is easy to use.

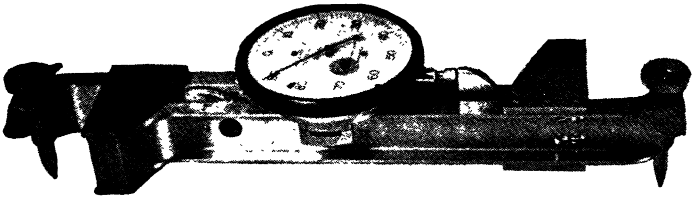


FIG. 90. Whittemore 10-in. strain gage. Plate fulcra permit gage points to move without magnification. Dial reads directly to 0.0001 in.

Most mechanical gages are of the portable type, so that one instrument may be used for many gage lines. After an observation has been made at one gage line, the strain gage is shifted to another and then another until all readings have been obtained. To ensure results that agree with one another when duplicate readings are taken the gage holes must be carefully prepared. In Figure 91 are shown good and bad gage holes. The shallow hole will obviously permit the point of the gage to move, within limits, in either direction and thus introduce variation in the results. Gage holes are laid out with a gage punch set for the length of the strain gage to be used. The surface on which strain is to be measured is punched lightly with this laying-out punch and the holes are then drilled with a No. 60 or similar drill. In some cases it is possible to make a satisfactory impression in the test surface with a punch more sharply pointed than the gage points. To obtain strain measurements in wood or plywood it is necessary to drive small tacks into the wood and place the gage holes in the tack heads, using one tack for each gage hole, or to glue small, previously drilled, metal plates to the wood surface. This latter method must be followed if the plywood or wood is so thin that a tack would affect the test result.

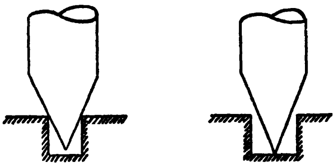


FIG. 91. Good (*left*) and bad strain gage holes.

The sequence to be observed when using mechanical gages is as follows:

1. Obtain initial reading of the gage line as the average of two observations.* These observations must check one another within limits of

---

* Good strain gaging technique demands that, for impartial results, the observer make observations on all gage lines in some rotative order and read only once for each line. The round of observations is then repeated and any lack of check in readings noted by the recorder. When the second round of observations has been completed the recorder should request additional readings for those gage lines which did not check. This procedure is re-

variation consistent with the multiplication ratio of the instrument and the modulus of elasticity of the material.

2. Obtain a reading for the gage line for the specified load. The reading is the average of two observations.

3. Determine the difference between the average readings by subtracting the initial from the final reading. This is the strain for the increment of load applied.

4. The stress is then

$$s = \frac{\text{difference} \times \text{modulus of elasticity}}{\text{multiplication ratio} \times \text{gage length}}$$

$$s = \text{difference} \times \left(\frac{E}{mL}\right) = \text{difference } (K)$$

in which K = a constant for the material and strain gage.

When the proportional elastic limit is exceeded, this relationship obviously does not hold. If the tangent modulus is known the stresses may be evaluated using this property. It is advisable to have the stress-strain diagram for the material with which the strain gage is to be used so that the limit of gaging may be realized, or so that stresses beyond the proportional elastic limit may be evaluated from the diagram.

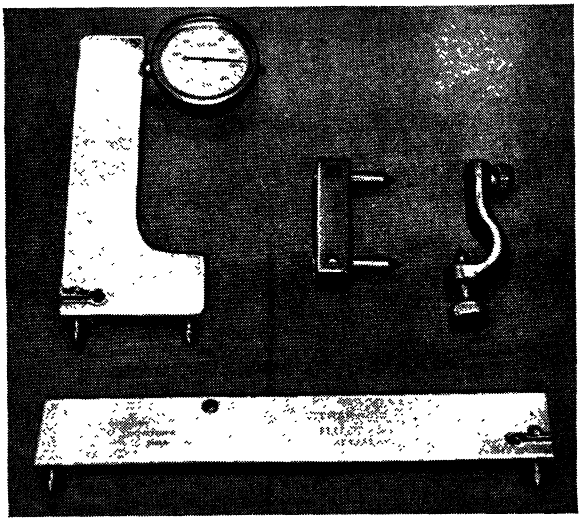


FIG. 92. Berry strain gage types, 2-in. above with dial attached; 8-in. below with dial removed. Two-inch laying-out punch and specimen clamp shown in upper right.

When the Whittemore strain gage is placed in the gage holes it should be rocked slightly in a direction transverse to the length to seat the gage

peated until satisfactory agreement is obtained for all gage lines. The recorder should never have the observer repeat a reading immediately, since the observer will unconsciously be influenced by the previous reading.

points in the holes. For lever type mechanical gages, the movable gage point should be inserted into a hole first and the fixed point then moved in the proper direction to the other gage hole. It is imperative that uniform pressure be applied to the gage while making observations. This is easily done when the gage line is horizontal and on such a surface that downward pressure can be applied. In the vertical position it is more difficult to obtain uniform pressure. The overhead position offers the greatest difficulty, and it is gage lines of this type that most frequently require checking.

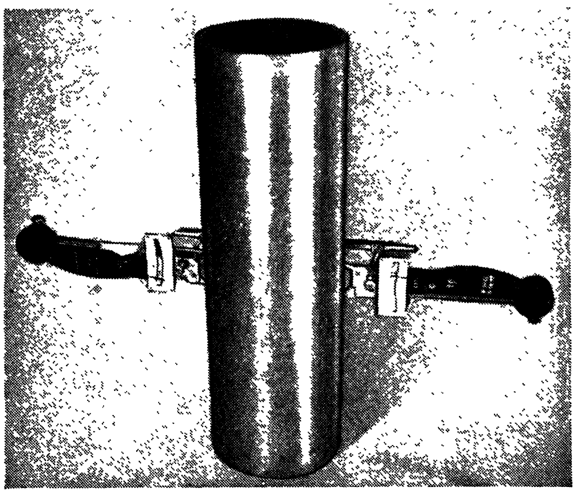


FIG. 93. Machined tubular specimen showing Huggenberger tensometers attached with clamps. The same specimen may also provide gage holes for mechanical gages of from 2-in. to 10-in. gage lengths.

Mechanical gages often employ levers to magnify the strain. This is necessary on small gage lengths or when the indicating dial does not measure to 0.0001 in. The Berry strain gage shown in Figure 92 is of this type. A more sensitive instrument of the lever type is the Huggenberger tensometer shown attached in different positions in Figures 93 and 94.

If strain gage readings are obtained over a long period of time it may be necessary to make correction for temperature changes. Frequent readings made on a standard bar of Invar steel (low coefficient of thermal expansion) will help detect any temperature effect. For extreme variation in temperature, correction may be made on the basis of the coefficient of thermal expansion for the material.

Electrical strain gages may be attached or portable, depending on the type. The general classes are as follows:

1. *Resistance.* The electrical resistance of certain alloy steel wires changes rapidly when the wire is strained. This fact is employed in the resistance strain gages shown in Figure 95. The change in resistance

mine change of length, or strain. Gages of this type are often used for insertion in couplings or connections of large size to measure applied forces. They are portable but generally not small in size.

Optical strain gages make use of the principle of the optical lever, as shown in Figure 96. The Martens mirror extensometer and the Tuckerman optical strain gage are of this type. The Martens instrument is essentially a laboratory device to determine strain for extremely precise stress-strain data and is not so adaptable to strain gaging as are the instruments previously described. The Tuckerman optical strain gage is an instrument that uses the optical lever principle and yet is small enough to be adaptable for strain gaging as well as securing stress-strain data. The optical lever gages have the disadvantage of not being rugged so that, when moved about and attached in many locations or to parts that may be jarred in loading, they may be damaged.

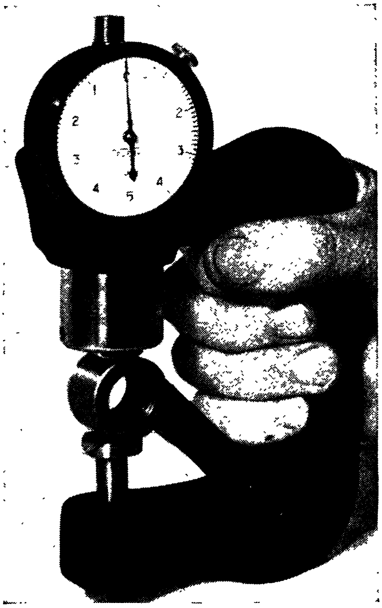


Fig. 97(a). Dial indicator held in fixture for use as a snap gage. (Courtesy Federal Products Corporation)

The mechanical gages, optical lever gages, and portable electrical gages (carbon pile and inductance) must be calibrated for accuracy. This operation may be done with an accurate micrometer lead screw and attached indicating head, with precision gage blocks, or with a strainometer comparator as designed by the National Bureau of Standards. The calibration of gages will not be included in this experiment.

One of the most versatile testing tools available is the dial indicator, or *dial gage,* as it is commonly called. It has been shown previously that it may be adapted to strain gages, torsion meters, extensometers, and deflection indicators for beam tests. Gages with 1 in. of travel usually have a least count of 0.001 in. (one dial division = 0.001 in.) and revolution counters to indicate the tenths. The more accurate 0.0001-in. dials have only a short travel, usually less than 0.20 in. Actually, the travel of a dial gage stem has little meaning, since the gage may always be moved to a new position, a new datum or reference point established, and the readings continued from this new zero point. Dial gages are also extremely useful in inspection work, as may be seen from the few uses illustrated in Figures 97(a) and (b).

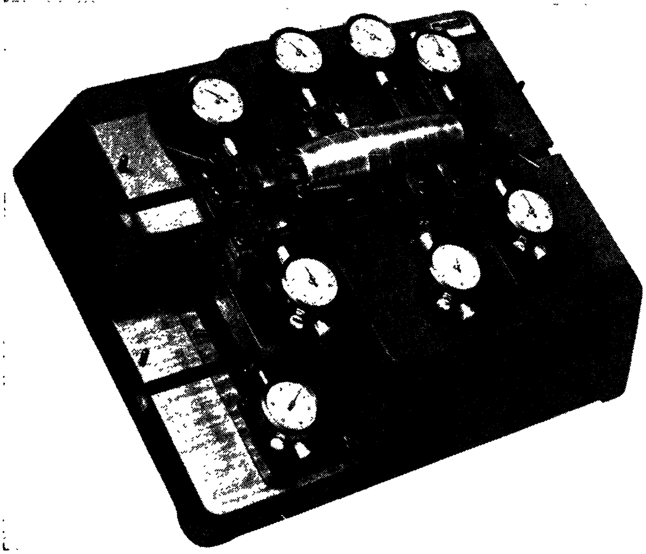


FIG. 97(b). Dial indicators used on gage for testing five inside and three outside diameters for concentricity of shell body. (Courtesy Federal Products Corporation)

INTERPRETATION OF STRAIN GAGE DATA

It has been shown previously that a single axial load applied to a unit cube of material will cause two sets of internal stresses, a normal stress governed by the applied load (such as tension or compression) and, as a result of the direct load, shearing stresses. It can further be shown that, regardless of the loading combinations applied to a part, at any point there are three mutually perpendicular planes on which the stresses are normal to the plane and on which no shearing stresses exist. These normal stresses are called principal stresses and are important in engineering design. Often one of the principal stresses is zero and occasionally two are zero.

From mechanics of materials it can be shown that the maximum shearing stress at any point is equal to one half the difference between the maximum and minimum principal stresses

$$s_s\ (\text{max}) = \frac{s\ (\text{max}) - s\ (\text{min})}{2}$$

in which s = tensile or compressive stress with tension considered minus. The difference between the stresses is thus the algebraic difference.

This maximum shearing stress will occur on the two planes that bisect the angles between the principal planes. To find the angle on which the principal stresses act, refer to Figure 98 and the following relationship

$$\tan 2\theta = \frac{2s_s}{s}$$

in which s = tensile or compressive principal stress.

Since the tangents of angles are equal for two angles of 2θ 180° apart, or θ 90° apart, the above stress exists on two planes perpendicular to each other. The direction in which θ should be measured can easily be determined by inspection.

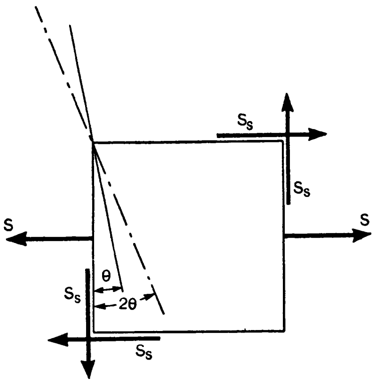


FIG. 98. Principal stresses act on a plane θ degrees from the axial plane.

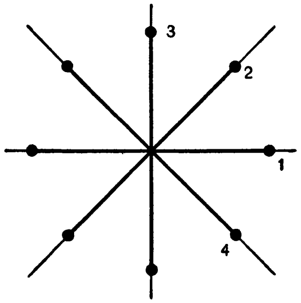


FIG. 99. Strain gage rosette pattern of the rectangular type.

Strain gage lines are often laid out in a rosette pattern as shown in Figure 99. Only the gage lines 1, 2, and 3 are needed but the fourth is often taken as a check on line 2. By measuring the strains in three directions the principal strains and thus the principal stresses and their line of action may be found. This knowledge is required in stressed skin design of aircraft, stiffened flat sheet construction, and other sections where the load is bi-axially or multi-axially applied. In such a case the directions of the principal stresses are not known as they had been assumed in the previous relationship. The observed data may be converted to principal strains or stresses by an exact analysis or by a graphical analysis. In Figure 100

$$\epsilon_{Px} = \epsilon_x \cos^2 \theta + \epsilon_y \sin^2 \theta + \epsilon_{xy} \sin \theta \cos \theta$$

in which ϵ_{Px} = the principal strain nearest in angular displacement to the x axis.
ϵ_x and ϵ_y = strains along the coordinate axes, x and y.
ϵ_{xy} = the shearing strain, which is actually the change in angle of the coordinate axes.

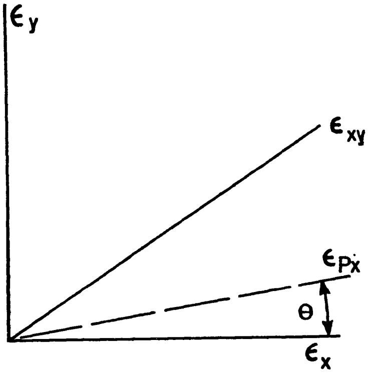


Fig. 100. Relation of principal to measured strains.

The angle θ is positive when measured in the counterclockwise direction from the x axis. When the strains ϵ_x, ϵ_{xy}, and ϵ_y are measured along 0°, 45° and 90° angles, respectively, with the x axis, this relationship gives three expressions, one for each of these angles. They are

$\epsilon_x = \epsilon_1$, the actual strain measured along gage line 1.
$\epsilon_y = \epsilon_3$, the actual strain measured along gage line 3.
$\epsilon_{xy} = 2\epsilon_2 - (\epsilon_1 + \epsilon_3)$, ϵ_2 being the actual strain measured along gage line 2.

The principal strains are related to the components of these strains as follows:

$$\epsilon_P = \tfrac{1}{2}(\epsilon_x + \epsilon_y) \pm \tfrac{1}{2}\sqrt{(\epsilon_x - \epsilon_y)^2 + \epsilon_{xy}{}^2}$$

in which ϵ_P = principal strain. For ϵ_{Py}, the principal strain nearest in angular displacement to the y axis, the second term is minus.

Substituting the values for ϵ_x, ϵ_y, and ϵ_{xy} in this relationship the principal strains will be

$$\epsilon_{Px} = \tfrac{1}{2}(\epsilon_1 + \epsilon_3) + \tfrac{1}{2}\sqrt{(\epsilon_1 - \epsilon_3)^2 + [2\epsilon_2 - (\epsilon_1 + \epsilon_3)]^2}$$

which reduces to

$$\epsilon_{Px} = 0.5[(\epsilon_1 + \epsilon_3) + 1.41\sqrt{(\epsilon_1 - \epsilon_2)^2 + (\epsilon_2 - \epsilon_3)^2}]$$

and for the other principal strain the simplified expression is

$$\epsilon_{Py} = 0.5[(\epsilon_1 + \epsilon_3) - 1.41\sqrt{(\epsilon_1 - \epsilon_2)^2 + (\epsilon_2 - \epsilon_3)^2}].$$

To find the principal stresses from these principal strains it is necessary to convert strain to stress, using the relationship $E = s/\epsilon$, and correct for transverse strain with Poisson's ratio. Thus

$$\epsilon_{Px} = \frac{s_{Px}}{E} - \frac{s_{Py}}{E}\mu$$

$$\epsilon_{Py} = \frac{s_{Py}}{E} - \frac{s_{Px}}{E}\mu.$$

Solving for s_{Px} and s_{Py} gives

$$s_{Px} = E\frac{(\epsilon_{Px} - \epsilon_{Py}\mu)}{(1 - \mu^2)}$$

$$s_{Py} = E\frac{(\epsilon_{Py} - \epsilon_{Px}\mu)}{(1 - \mu^2)}.$$

When the expressions previously given for principal strains in terms of the observed strains are substituted in these equations the principal stresses are found to be

$$s_{Px} = E\left[\frac{0.5(\epsilon_1 + \epsilon_3)}{(1 - \mu)} + \frac{0.71\sqrt{(\epsilon_1 - \epsilon_2)^2 + (\epsilon_2 - \epsilon_3)^2}}{(1 + \mu)}\right]$$

$$s_{Py} = E\left[\frac{0.5(\epsilon_1 + \epsilon_3)}{(1 - \mu)} - \frac{0.71\sqrt{(\epsilon_1 - \epsilon_2)^2 + (\epsilon_2 - \epsilon_3)^2}}{(1 + \mu)}\right].$$

These relationships hold only for an isotropic material (E the same in all directions) and for stresses below the proportional elastic limit. In these relationships tension should be taken as plus and compression as minus. To find the maximum shearing stress or the angles of the principal stresses with respect to the strain rosette pattern use the relationships for s_s (max) and θ previously given.

The summarized derivation * of these relationships is given so that the method may be adapted to gage patterns other than the rectangular rosette used here. The equiangular strain gage rosette pattern is often used with characteristic patterns similar to those shown in Figure 101. Equations of the above types are most readily solved by a tabular form,

---

* For a complete derivation of the formulas used in either the rectangular or equiangular type of strain rosette pattern, as well as graphical solutions for either case, the student should refer to "Photoelasticity," by M. M. Frocht, John Wiley and Sons, 1941, pp. 33-40. Additional references are "The Equiangular Strain Rosette," R. D. Mindlin, *Civil Engineering,* Vol. 8, No. 8, Aug., 1938, pp. 546-548; "Determination of Principal Stresses from Strains on Four Intersecting Gage Lines 45° Apart," W. R. Osgood, *Journal of Research,* United States Bureau of Standards, No. 6, Dec., 1935, pp. 579-581; "Interpreting Data from Strain Rosettes" and "Strain Rosette Technique," G. E. Beggs and E. K. Timby, *Engineering News Record,* Mar. 10, 1938, pp. 366-370, and Mar. 17, 1938, pp. 404-406.

setting up the denominator terms involving Poisson's ratio as a constant for the material used.

Obviously this manner of solving for principal stresses and planes of stress may be followed regardless of the type of gage with which the strains in the rosette pattern were determined. The electrical gages shown in Figure 95 are manufactured with the rosette pattern explained here (0°, 45°, and 90° gage lines).

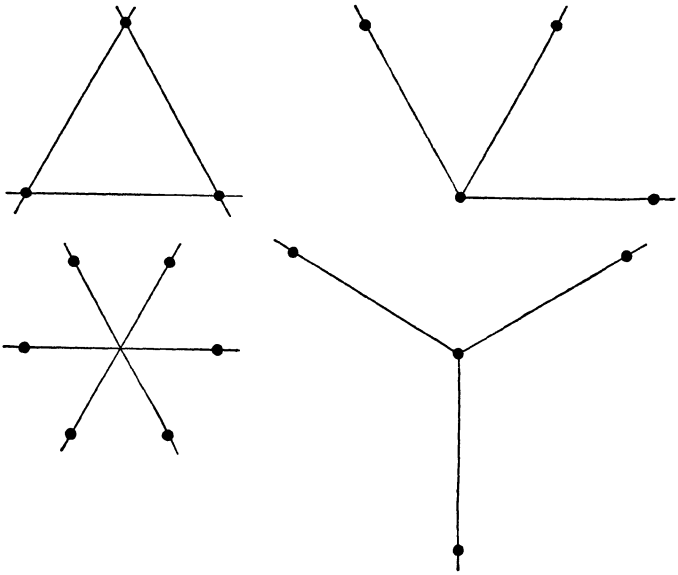


FIG. 101. Strain gage rosette patterns of the equiangular type.

This experiment is intended to acquaint the student with various types of strain gages, the technique to be employed in their use, and the actual interpretation of the results.

EXPERIMENTAL PROCEDURE

APPARATUS—Various strain gages (of as many types as available), laying out punch, No. 60 drill, Universal testing machine, and flexure testing apparatus.

MATERIAL—Threaded end tension specimen having a reduced portion about 8 in. longer than the gage length of the strain gage to be used with it. Tubular compression specimen with ends machined flat and perpendicular to the longitudinal axis of the tube (see Figure 93). Steel or aluminum 12-in. standard I-beam section or any other type of flexure specimen, such as a small truss. If a flat plate or stiffened flat sheet is available for compression tests it may be used if the ends are flat and perpendicular to the longitudinal axis of the specimen. Many machine, structural, or aircraft parts may readily be adapted to strain gage analysis.

Strain gages may be used as extensometers with which to obtain strain data and the stress-strain diagram. The tension specimen is ideally suited to this work and will be used within the proportional elastic limit in this test to illustrate the manner in which the modulus of elasticity may be obtained. Measure the diameter of the specimen and calculate the load that will produce a stress in it equal to the proportional elastic limit of the material. Divide this load into six equal increments from zero to the maximum. Lay out four gage lines along the specimen, each separated by 90°. Following the technique previously outlined, secure gage readings for each gage line at all increments of load and record all observations on a data sheet similar to the sample shown. Convert the loads to stress using the original cross-sectional area.

The same procedure should be repeated for the compression specimen. If a stiffened flat sheet or heavy flat sheet is used for the compression specimen, several strain rosette patterns may be laid out on each face. The position of all gage lines with respect to the direction of load should be shown on the data sheet. The modulus of elasticity in compression may or may not be determined as desired.

A flexure specimen made of a structural I-beam section is ideal to il-

EXPERIMENT 14 — STRAIN GAGES AND THEIR USE

STRAIN GAGE ______ GAGE LENGTH ______ MULTIPLICATION RATIO ______

NAME ______ OBSERVER ______ RECORDER ______

STRAIN MEASUREMENTS OF ______

LOAD	SERIES	DATE	TIME-STARTED	TEMPERATURE	TIME-FINISHED	GAGE LINE	STD. BAR									
						ZERO	INITIAL	FINAL								
						OBSERVATION										
						OBSERVATION										
						UNCORRECTED AVG.										
						CORRECTION										
						CORRECTED AVG.										
						CORRECTED DIFF.										
						UNIT DEFORMATION										
						STRESS										
						OBSERVATION										
						OBSERVATION										
						UNCORRECTED AVG.										
						CORRECTION										
						CORRECTED AVG.										
						CORRECTED DIFF.										
						UNIT DEFORMATION										
						STRESS										
						OBSERVATION										
						OBSERVATION										
						UNCORRECTED AVG.										
						CORRECTION										
						CORRECTED AVG.										
						CORRECTED DIFF.										
						UNIT DEFORMATION										
						STRESS										

Sample data sheet for Experiment 14.

lustrate the versatility of the strain gage. Gage lines should be laid out along the edges and centers of the top and bottom flanges and in the web. Strain rosette patterns laid out on the web should be symmetrical about the neutral axis and should be located at the mid-span, quarter or third points, and immediately over the supports. The locations of all gage lines should be shown on a sketch to be placed on the data sheet. Secure the moment of inertia of the cross section for the I-beam used from a structural handbook and calculate the maximum load the beam can support without permanent deformation. Use the flexure formula $s = Mc/I$ and a value for s corresponding to the proportional elastic limit of the material. Divide this load into six equal increments from zero to the maximum. Record the strain gage observations for each load on the data sheet.

Preparation of Report

COMPUTATIONS

The data sheet should provide for converting the observed data to stress. Other computations for theoretical stresses in the beam or for principal stresses should be made on computation sheets similar to the samples shown. Also sketch the moment diagram at the maximum load in the space shown on the computation sheet. Compare the observed stresses with those calculated by the ordinary design formulas and give the percentage error in each case. When principal stresses are calculated determine also the angles which they make with respect to some reference line.

EXPERIMENT 14

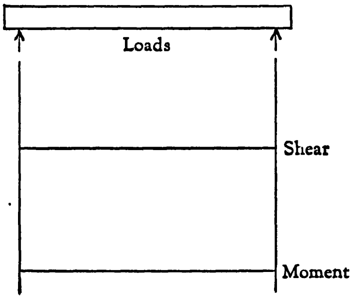
COMPUTATION SHEET NO. 1

Material____________________Type of specimen________________________

Strain gage____________________Gage length__________Multiplication factor__________

Name____________________ Date____________________

Flexure Specimen



Loading and moment diagrams at maximum load

Sample computation sheet Number 1 for Experiment 14.

EXPERIMENT 14

COMPUTATION SHEET NO. 2

Material________________________**Type of specimen**____________________

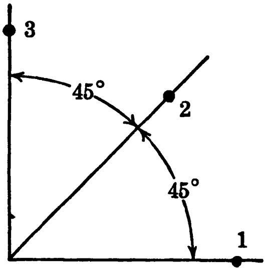
Strain gage____________________**Gage length**__________**Multiplication factor**________

Name__________________________________ **Date**____________________

Determination of Principal Stresses

$$s_{P_x} = E\left[\frac{0.5\,(\epsilon_1 + \epsilon_3)}{(1-\mu)} + \frac{0.71\sqrt{(\epsilon_1-\epsilon_2)^2 + (\epsilon_2-\epsilon_3)^2}}{(1+\mu)}\right]$$

$$s_{P_y} = E\left[\frac{0.5\,(\epsilon_1 + \epsilon_3)}{(1-\mu)} - \frac{0.71\sqrt{(\epsilon_1-\epsilon_2)^2 + (\epsilon_2-\epsilon_3)^2}}{(1+\mu)}\right]$$



Location of gage lines for rectangular rosette

Sample computation sheet Number 2 for Experiment 14. Poisson's ratio may be taken as 0.28 for steel and 0.33 for aluminum.

DETERMINATION OF MODULUS OF ELASTICITY

Using the average strain observed at the four gage lines for each stress, plot the stress-strain diagram for tension or compression over the range of data obtained. Cross-section paper for this plot should follow the pattern of the sample shown. From this straight line relationship calculate the modulus of elasticity of the material.

DISCUSSION

1. In the following tables compare the observed and calculated stresses and determine the error as indicated:

Tension or Compression Specimen:

Load, lb.	Average stress from four gage lines, psi.	Calculated stress from $s = P/A$, psi.	Error,* per cent

---

* **Assuming $s = P/A$ to be correct.**

Account for the observed errors.

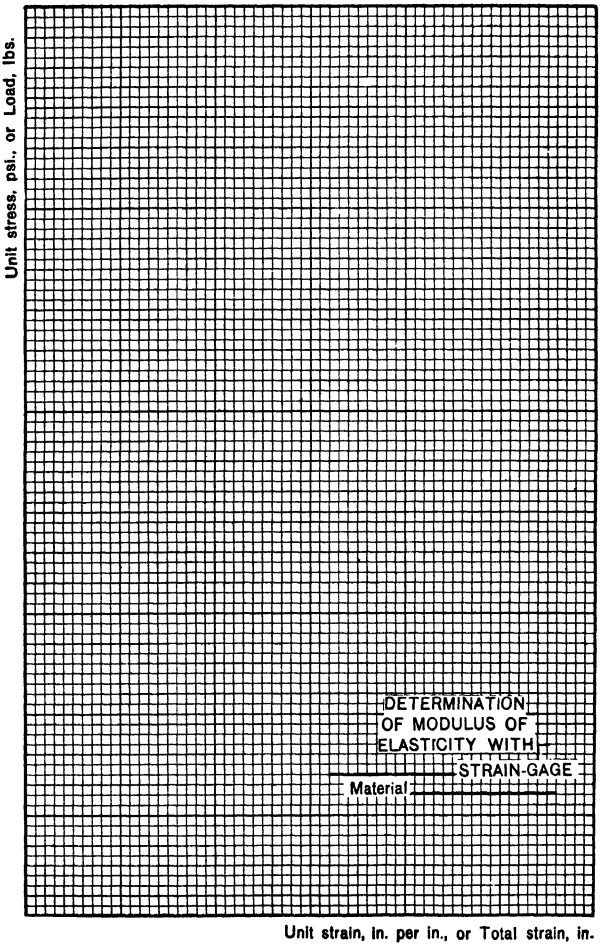
Flexure Specimen:

	Average stress from similar gage lines, psi.				Stress from design formulas, psi.			
Load, lb.	*	*	*	*	*	*	*	*

* Indicate location in beam at which stresses were measured.

Do the stresses calculated with the design formulas agree with the observed stresses? Why?

2. It is desired to check the dead and live load stresses in a bridge that is to be built. Explain the steps to be followed if mechanical strain gages are to be used.
3. The stress in a machine part under load is calculated from strain gage data to be 51,500 psi. An examination of the stress-strain diagram for the material shows the proportional elastic limit to be 45,900 psi. Is the calculated value correct? Why?
4. How might the stress in question 3 be calculated using the observed strain and the stress-strain diagram?


Unit stress, psi., or Load, lbs.
DETERMINATION OF MODULUS OF ELASTICITY WITH
STRAIN-GAGE
Material
Unit strain, in. per in., or Total strain, in.

Sample sheet of cross-section paper for Experiment 14, showing how strain gage data may be used to determine modulus of elasticity. Appropriate legend and scale to be selected and filled in for each coordinate axis.

EXPERIMENT 15

TENSION, COMPRESSION AND SHEAR TESTS OF WOOD

By varying the size of a wood beam specimen it is possible to determine the strength of wood in tension, compression, or shear, as has been shown in Experiment 5. These properties may more readily be evaluated directly from actual tests for each condition, however, and the results thus obtained applied to beam design. The student should again refer to Experiment 5 for the importance of each form of stress in such design.

This experiment is intended to acquaint the student with the physical properties of various woods, including the modulus of elasticity in compression, the manner of failure under each kind of loading, and the severity of this failure.

Experimental Procedure

APPARATUS—Universal testing machine, compressometer, shear tool for wood, tapered tension grips (depending on specimen), spherical bearing block, 12-in. scale, and calipers.

MATERIAL—Tension, compression, and shear specimens of several types of common woods, conforming to governing A.S.T.M. specifications for size in so far as possible and consistent with the testing apparatus available.

Tension Test

Because wood is weak in compression perpendicular to the grain it is difficult to make a tension test and have the failure occur away from the grips. For this reason it is necessary to use a special type of tension specimen and grips as shown in Figure 102, or A.S.T.M. Designation D143-27,

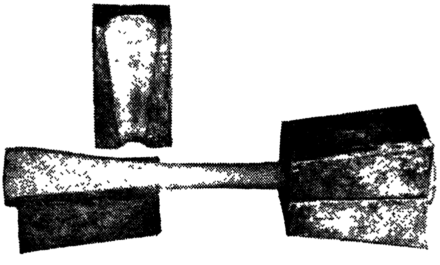


Fig. 102. Tapered tension specimen for wood. Special grips also shown.

or later. Obtain the dimensions of the specimen, place it in the grips in the testing machine, and load to failure. Observe the type of failure and record the maximum load on the data sheet.

EXPERIMENT 15

TENSION COMPRESSION, AND SHEAR TESTS OF WOOD

Name______________________________ **Date**________________

TENSION TESTS

Material					
Diameter, in.					
Area, sq. in.					
Maximum load, lb.					
Tensile strength, psi.					
Fracture type					

SHEAR TESTS

Material					
Direction of grain*					
Dimensions, in.					
Area in shear, sq. in.					
Maximum load, lb.					
Shearing strength,psi					

*** With reference to load**

Additional Tests: (Data sheet may be expanded for additional tests)

Sample data sheet Number 1 for Experiment 15.

Shear Test

The shear tool should consist of a clamp to hold the specimen firmly and a loading edge with which to apply a single shearing load. Such a shear tool with a specimen in place is shown in Figure 103 and also in A.S.T.M. Designation D143-27, or later.

Measure and record the specimen dimensions and direction of grain. Apply load to the loading edge, as shown in Figure 103, through the flat head of the testing machine. Record the breaking load and the direction of the failure with respect to the direction of grain. It is preferred that the grain be selected so as to conform to the two variations, shear perpendicular to grain and shear parallel to grain. If the failure at the base of the specimen extends back onto the supporting surface the test must be repeated.

EXPERIMENT 15

TENSION, COMPRESSION AND SHEAR TESTS OF WOOD

Name ______________________________ Date ______________

COMPRESSOMETER TEST OF WOOD PARALLEL TO GRAIN

Load, lb.	Stress, psi.	Compressometer dial readings				Total shortening, in.	Strain = Unit shortening, in. per in.
		Dial 1	Dial 2	Average	Corrected to zero		

Material ______________
Dimensions, in. ______________
Area, sq. in. ______________
Fracture type ______________

Annular rings per inch ______________
Percentage of summer wood ______________
Gage length of compressometer ______________

Sample data sheet Number 2 for Experiment 15.

Compression Test

A compressometer for wood is shown attached to a specimen in Figure 104. Another type is shown in A.S.T.M. Designation D143-27, or later.

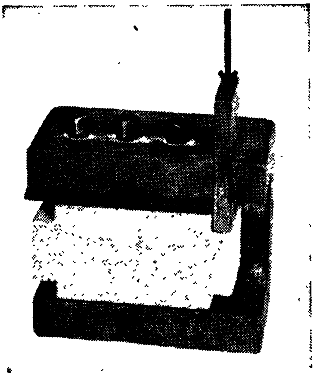


Fig. 103. Shear tool for wood. Note shape of specimen. Load applied as shown.

The dimensions of the specimen should be obtained to the nearest 0.01 in. and recorded on the data sheet. With the compressometer attached to the specimen a small initial load should be applied and the dials set to zero. Apply load in the increments given by the instructor, reading the dials at each load. The compressometer may be left in place and data obtained until the specimen fails. Wood in compression parallel to the grain usually fails in a horizontal plane by crushing or collapse of the longitudinal fibers. A failure of this type is shown in Figure 105. Other failures may be described as wedge split, shearing, splitting, or compression plus shearing parallel to grain (see A.S.T.M. Designation D143-27, or later). Record all observations on the data sheet.

If time permits, additional tests of wood for hardness, cleavage, shrinkage, specific gravity, moisture content, tension perpendicular to grain, and compression perpendicular to grain may be made following the methods outlined in A.S.T.M. Designation D143-27, or later.

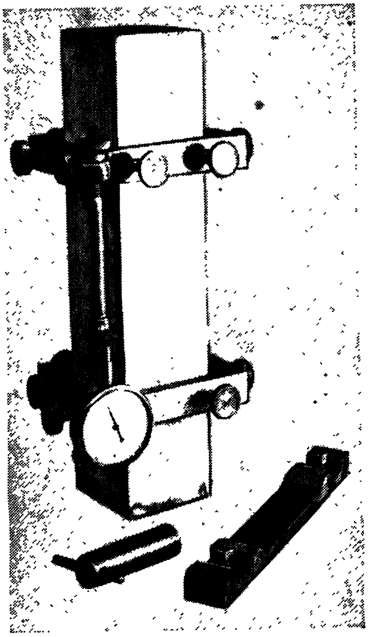


Fig. 104. Compressometer attached to wood specimen. Other dial gage does not show. Spacer bar and wrench shown in front of specimen.

Preparation of Report

COMPRESSIVE STRESS-STRAIN DIAGRAM

The observed data should be converted to stress and strain on the data sheet. The compression stress-strain diagram may be plotted on cross-section paper similar to the sample shown. Select suitable scales for stress and strain and mark these scales on the coordinate axes. Correction to zero strain may be made on the data sheet or on the curve sheet.

COMPUTATIONS

From the straight-line portion of the stress-strain diagram determine the modulus of elasticity and the stress at the proportional elastic limit. From these values calculate the modulus of elastic resilience. All other computations may be omitted and only the results shown on the data sheet.

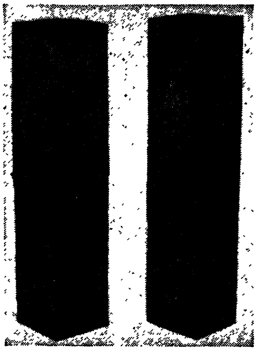


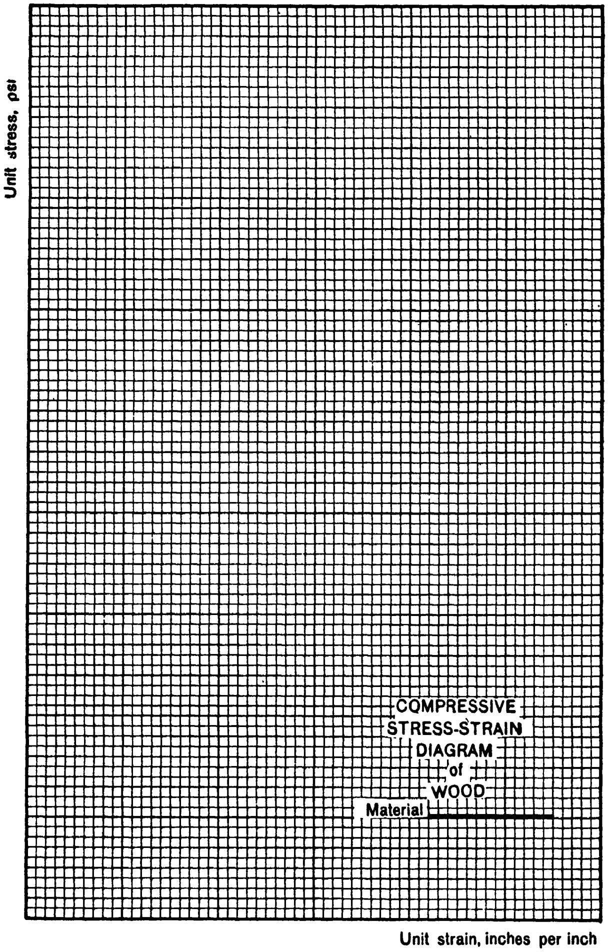
FIG. 105. Failure of wood in compression parallel to grain by crushing (*left*) and shearing (*right*). Specimens were coated with shellac on ends before testing to prevent brooming effect.

DISCUSSION

1. In the following table compare the test results with average values obtained from the instructor:

Material	Property	Test result	Average values

2. Account for wide differences between test and average values in question 1.
3. List the physical properties (strength only) of wood in their order of decreasing strength. Include tensile strength in both directions, shearing strength in both directions, and compressive strength in both directions. Circle the properties that will govern wood beam design and state why each is important.
4. In Figure 106 is shown a rectangular wood beam. The instructor will sketch this beam on the board and indicate the location of defects such as knots, checks, shakes, and cross-grain as well as the manner of loading. Transfer the location of these defects to a sketch similar to Figure 106 and analyze the beam. State whether the beam will or will not support the type of load imposed on it and give reasons for the opinion expressed. Use small sketches if necessary and the information in question 3.



Sample sheet of cross-section paper for compressive stress-strain diagram of wood in Experiment 15. Coordinate scales to be filled in.

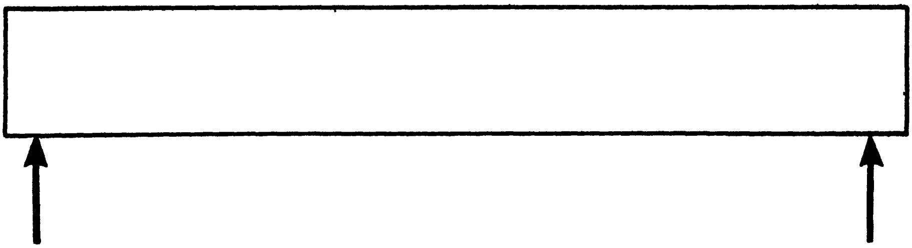


FIG. 106. Defects in beam (to be filled in by student as directed by the instructor) influence its resistance to failure.

EXPERIMENT 16

EFFECT OF MOISTURE UPON THE FLEXURAL PROPERTIES OF WOOD

Freshly cut green timber may have a moisture content as high as 35 per cent, which may be reduced to 4 per cent by kiln drying, but ordinarily is found to be from 10 to 15 per cent in commercial grades of lumber. Wood fibers will absorb water up to a saturation point of from 25 to 30 per cent, depending upon the density and structure of the wood. The amount of water has considerable effect upon the physical properties of wood, an effect which can most readily be shown by the flexure test.

This experiment is intended to analyze quantitatively the manner in which moisture affects the flexural properties of wood.

EXPERIMENTAL PROCEDURE

APPARATUS—Universal testing machine with tapered bearing supports for small beams, deflectometer, 12-in. scale, and calipers.

MATERIAL—Four beam specimens for each kind of wood studied. Specimens of the same weight (specific gravity) should be used. The original weight of each specimen, in grams, should be stamped on it. Specimens, with the exception of one unsoaked specimen, should be allowed to soak for different periods of time so that they will vary in moisture contents when tested. The span of the beams may vary from 24 to 30 in. and the cross-sectional dimensions should be about 1.5 by 2 in.

Weigh each beam and record on the data sheet both the initial weight stamped on the wood and the final weight. One specimen will not be soaked in water and will be considered the base specimen with which to compare all values of strength and stiffness. Measure the dimensions to the nearest 0.01 in. The specimens should be placed on the end bearing blocks with small bearing plates between the specimen and the tapered edges of the bearing blocks. The longest dimension should be vertical.

A deflectometer may be made from a dial gage as shown in Experiment 5. It might also be a portion of a special beam testing machine, or it may be a lever type of instrument which can be placed under the beam. Regardless of type it should give deflection to 0.01 in. The completed test set-up should follow that outlined in A.S.T.M. Designation D143-27, or later.

Apply a concentrated load at mid-span and note the applied load at each 0.05-in. increment of center-line deflection. Continue to apply load and observe the deflection until the load for each increment of deflection has decreased materially and the specimen is well beyond its proportional elastic limit. Remove the deflectometer and continue increasing the load to failure. Record on the data sheet the maximum load and the type of failure.

Repeat this procedure for all beams and for all woods studied.

EXPERIMENT 16

EFFECT OF MOISTURE UPON THE FLEXURAL PROPERTIES OF WOOD

Name ______________________ Date ______________

Material ______________________ Span ______________

Specimen 1	Specimen 2	Specimen 3	Specimen 4
Dimensions, in. ______ Volume, cu. in. ______ Original wt. ______ Final wt. ______ Moisture, per cent ______ Fracture type ______	Dimensions, in. ______ Volume, cu. in. ______ Original wt. ______ Final wt. ______ Moisture, per cent ______ Fracture type ______	Dimensions, in. ______ Volume, cu. in. ______ Original wt. ______ Final wt. ______ Moisture, per cent ______ Fracture type ______	Dimensions, in. ______ Volume, cu. in. ______ Original wt. ______ Final wt. ______ Moisture, per cent ______ Fracture type ______

Mid-span load, lb.	Mid-span deflection		Mid-span load, lb.	Mid-span deflection		Mid-span load, lb.	Mid-span deflection		Mid-span load, lb.	Mid-span deflection	
	Reading	Total, in.		Reading	Total, in.		Reading	Total, in.		Reading	Total, in.

Sample data sheet for Experiment 16.

PREPARATION OF REPORT

LOAD-DEFLECTION DIAGRAMS

Plot the load-deflection diagram for each specimen on a single sheet of cross-section paper similar to the sample shown in Experiment 5. Select scales for load and deflection so that the curves occupy most of the sheet. Show these scales on the coordinate axes.

COMPUTATIONS

From the load-deflection curves or from the observed data calculate the following properties:

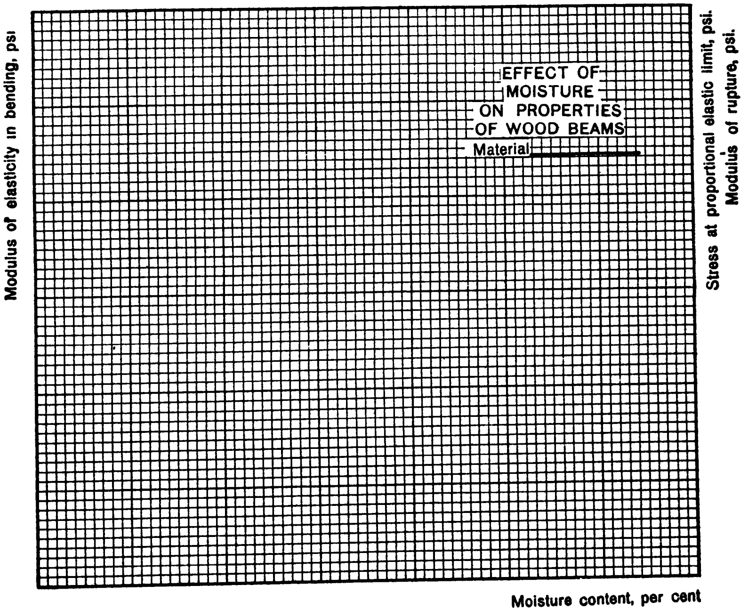
Specimen	Fiber stress at proportional elastic limit, psi.	Modulus of elasticity, psi.	Modulus of rupture, psi.

PROPERTY-MOISTURE CURVE

On a sheet of cross-section paper similar to the sample shown plot the relationship between the moisture content and each of the physical properties computed above. Select scales and indicate them clearly on the coordinate axes, distinguishing between different scales and different curves. Draw smooth curves through the plotted points.

DISCUSSION

1. Why is the bearing plate necessary under the beam at the supports, particularly in these tests?
2. Using the load-deflection diagrams prove which of the beams tested would make the best spring.
3. Were the compressive or tensile properties altered most by the increase in moisture? Why?


Modulus of elasticity in bending, psi
EFFECT OF
MOISTURE
ON PROPERTIES
OF WOOD BEAMS
Material
Stress at proportional elastic limit, psi.
Modulus of rupture, psi.
Moisture content, per cent

Sample sheet of cross-section paper to show effect of moisture content on various properties of wood in flexure in Experiment 16. Coordinate scales to be filled in.

EXPERIMENT 17

TEST OF A HELICAL SPRING

A helical spring subjected to axial loading is stressed essentially the same as a torsion specimen. Flexural, cross shear, and direct stresses are also present. Some of the spring's ability to absorb energy is due to its shape while the remainder is due to properties of the material of which the spring is made. The deflection of a helical spring may be expressed as

$$\Delta = \frac{8P(d)^3 n}{E_s(d_w)^4}$$

in which Δ = deflection of the spring, in.
P = applied axial load, lb.
d = mean diameter of the spring, in.
n = number of turns of the spring over which the deflection is measured.
E_s = modulus of elasticity in shear, psi., or modulus of rigidity, psi.
d_w = diameter of the spring wire, in.

The shearing stresses set up in the coils of the spring may be found from

$$s_s = \frac{8Pd}{\pi(d_w)^3}$$

in which s_s = shearing stress in coil wire, psi. (see Experiment 6). P, d, and d_w same as before.

This experiment is intended to acquaint the student with the manner in which the physical properties of springs are determined, the nature of some of those properties, and how they may be determined by this type of test.

Experimental Procedure

APPARATUS—Universal testing machine equipped with flat head, strain gage or dial gage, micrometers, 12-in. scale, and dividers.

MATERIAL—A helical spring of such a number of turns and wire size as to give considerable deflection under load.

CAUTION: The spring should be fitted into the testing machine or held in such a manner that it will not fly out in case of excessive deflection or disturbance of the end supports.

A helical spring set up in a testing machine ready for test is shown in Figure 107. The wire diameter should be obtained with the micrometer as the average of several readings and the mean diameter of the coil may be obtained from the wire size and inside or outside measurement of the coil. The gage length should be chosen so that spring deflections are measured over a whole number of turns. Using the formula previously given determine the load which the spring will support and yet not be stressed beyond the proportional elastic limit in shear of the material of which it is made. (The proportional elastic limit of the spring material will be furnished by the instructor.) Divide this maximum load into ten equal increments beginning with zero. Apply each load and observe the deflection. If the spring is not stiff and the deflections are therefore very great, a 12-in. scale may be used with dividers, rather than the strain gage or dial gage. Release the load in ten equal increments staggered halfway between the increasing loads and again observe deflections. Record all data on a sheet similar to the sample shown.

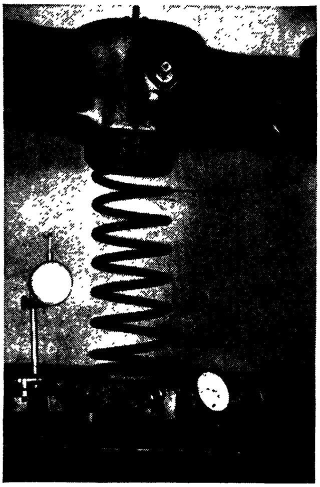


Fig. 107. Helical spring in place in testing machine. Deflection is measured over a whole number of turns as shown.

Preparation of Report

LOAD-DEFLECTION DIAGRAM

On cross-section paper similar to the sample shown plot the load-deflection diagram designating the increasing and decreasing loads by different symbols. Unless the points for increasing and decreasing loads differ by too wide a margin draw a straight line through the average of the points.

COMPUTATIONS

From the observed data or the load-deflection diagram compute the following:

1. The spring modulus, as the load required to deflect it elastically 1 in.
2. The spring modulus per turn, as the load required to deflect one turn of the spring elastically 1 in. (spring modulus per turn = the number of turns times the spring modulus).
3. The shearing stress in the coil wire at the maximum load.
4. The modulus of rigidity or modulus of elasticity in shear from the relationship given for deflection of the spring.

EXPERIMENT 17

TEST OF A HELICAL SPRING

Name ______________________ Date ______________

Mean diameter of spring, in. ______________

Number of turns over which deflection is measured ______________

Diameter of spring wire, in. ______________

Deflections measured with ______________

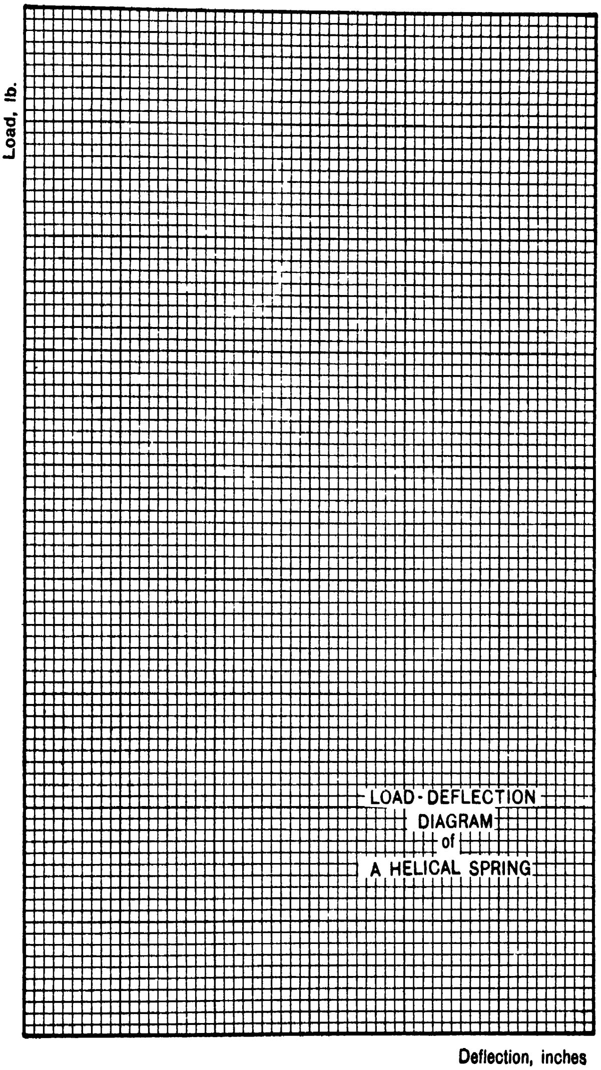
Gage length ______________

Increasing Loads			Decreasing Loads		
Load, lb.	Deflection		Load, lb.	Deflection	
	Reading	Total, in.		Reading	Total, in.

Sample data sheet for Experiment 17.

DISCUSSION

1. How does the modulus of elasticity in shear obtained in computation 4 compare with the value obtained for this property in Experiment 6? Account for any great difference.
2. Which would be most efficient for absorbing energy elastically, a helical spring or a rectangular beam, both of the same material? Why?
3. For equal stresses compare the amount of energy which can be stored elastically in round bars of the same size equally stressed in tension and shear. Since the shearing properties of spring steel are about 0.6 of the tensile properties, how would this energy comparison be affected if each specimen were stressed to the proportional elastic limit?
4. How might this or any other spring be used with a hydraulic jack as an improvised testing machine?



Sample sheet of cross-section paper for load-deflection diagram of a helical spring in Experiment 17. Coordinate scales to be filled in.

EXPERIMENT 18

FLEXURAL TESTS OF DUCTILE AND BRITTLE MATERIALS

Brittle materials may satisfactorily be tested for specification requirements by means of a flexure test. A.S.T.M. Designation A48-41, or later, "Specifications for Gray Iron Castings," provides for an optional test to be made on a cast iron bar loaded as a beam. Other brittle materials, such as concrete, plastics, glass, and ceramic products may quickly be tested by the flexure method.

This experiment is intended to show the student why the flexure test is limited to brittle materials and what its limitations are when other properties are derived from the test.

EXPERIMENTAL PROCEDURE

APPARATUS—Universal testing machine with tapered bearing supports for small beams, deflectometer, 12-in. scale, and calipers.

MATERIAL—Cast iron beams conforming to A.S.T.M. Designation A48-41, or later, for size and span. Mild steel beams of the same size as the gray cast iron. Beams of other brittle material as mentioned above and all having approximately the same cross section and span. (Beams of rectangular cross section may be used but are seldom available for cast materials, such as gray cast iron.)

The test procedure should be the same as that outlined in Experiment 16 for wood beams, except that the bearing plates can usually be eliminated for rectangular specimens. The bearing plates may be small for the round metallic specimens and for most brittle non-metallic specimens. Load should be applied through a roller at mid-span as shown in Figure 108. On the basis of the static tensile strength of the brittle material determine from the flexure formula the maximum load which it will support. Divide this load into ten equal increments from zero to the maximum. Apply each increment of load and determine the mid-span deflection. Continue to apply load and measure deflections until the specimen breaks. Record on the data sheet the breaking load and the manner of failure.

Determine the load which the ductile specimen can support when the outer fibers are at the proportional elastic limit. Divide this load into six increments from zero to the maximum. Apply these loads and obtain the mid-span deflection for each load. When the maximum of these increments has been reached reduce the increment by one half and continue to apply load and read deflection. When the specimen is well out into its plastic range, as indicated by larger increments of deflection, stop applying load. Additional data beyond this point is not of value.

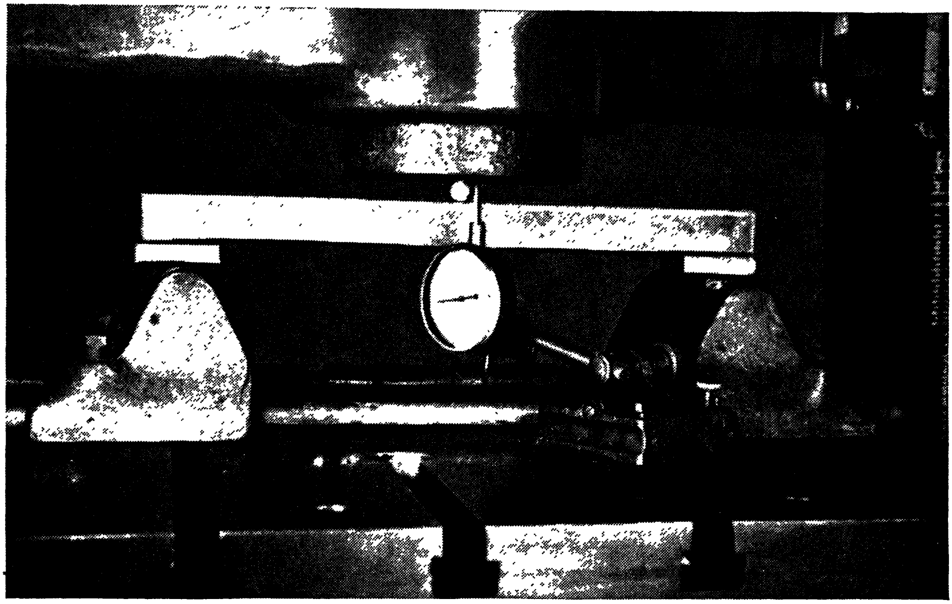


Fig. 108. Test set-up for flexural test of a brittle material (gray iron). Bearing plates need not be used for metallic specimens having a rectangular cross section.

Preparation of Report

LOAD-DEFLECTION DIAGRAMS

On cross-section paper similar to the sample shown in Experiment 5 plot the load-deflection diagram for each type of material. Indicate the scales used on the coordinate axes and show the limit of elastic beam action on each curve.

COMPUTATIONS

From the observed data or the load-deflection diagrams calculate the following:

1. Modulus of elasticity of each material in bending (use $\Delta = PL^3/48EI$).
2. Fiber stress at the proportional elastic limit.
3. Modulus of rupture of the brittle material.
4. Modulus of elastic resilience of the brittle and ductile materials at the same unit stress.

DISCUSSION

1. What is the ratio of the modulus of rupture of the brittle material to its tensile strength? If the ratio is not 1.0 discuss reasons why it is not.
2. What is the ratio of the modulus of rupture of the brittle material to its compressive strength?
3. At the same unit stress how do the brittle and ductile materials compare for elastic energy absorbing ability (E_r)? Account for any difference.
4. How do the ductile or brittle materials compare for modulus of elasticity in bending and in tension as obtained from previous experiments? Account for any great differences.
5. According to A.S.T.M. Designation A48-41, or later, in what class would the gray iron specimen be placed?

EXPERIMENT 18

FLEXURAL TESTS OF DUCTILE AND BRITTLE MATERIALS

Name ________________________________ Date ________________

<table>
<tr><td colspan="3">Material
____________</td><td colspan="3">Material
____________</td><td colspan="3">Material
____________</td><td colspan="3">Material
____________</td></tr>
<tr><td colspan="3">Dimensions, in. ______
Span, in. ______
Fracture type ______</td><td colspan="3">Dimensions, in. ______
Span, in. ______
Fracture type ______</td><td colspan="3">Dimensions, in. ______
Span, in. ______
Fracture type ______</td><td colspan="3">Dimensions, in. ______
Span, in. ______
Fracture type ______</td></tr>
<tr><td rowspan="2">Mid-span load, lb.</td><td colspan="2">Mid-span deflection</td><td rowspan="2">Mid-span load, lb.</td><td colspan="2">Mid-span deflection</td><td rowspan="2">Mid-span load, lb.</td><td colspan="2">Mid-span deflection</td><td rowspan="2">Mid-span load, lb.</td><td colspan="2">Mid-span deflection</td></tr>
<tr><td>Reading</td><td>Total, in.</td><td>Reading</td><td>Total, in.</td><td>Reading</td><td>Total, in.</td><td>Reading</td><td>Total, in.</td></tr>
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</table>

Sample data sheet for Experiment 18.

APPENDIX

TABLE OF CROSS-SECTIONAL AREAS FOR ROUND SPECIMENS

Dia.	Area	Dia.	Area	Dia.	Area	Dia.	Area	Dia.	Area
.101	.0080	.151	.0179	.201	.0317	.251	.0495	.301	.0712
.102	.0082	.152	.0181	.202	.0320	.252	.0499	.302	.0716
.103	.0083	.153	.0184	.203	.0324	.253	.0503	.303	.0721
.104	.0085	.154	.0186	.204	.0327	.254	.0507	.304	.0726
.105	.0087	.155	.0189	.205	.0330	.255	.0511	.305	.0731
.106	.0088	.156	.0191	.206	.0333	.256	.0515	.306	.0735
.107	.0090	.157	.0194	.207	.0337	.257	.0519	.307	.0740
.108	.0092	.158	.0196	.208	.0340	.258	.0523	.308	.0745
.109	.0093	.159	.0199	.209	.0343	.259	.0527	.309	.0750
.110	.0095	.160	.0201	.210	.0346	.260	.0531	.310	.0755
.111	.0097	.161	.0204	.211	.0350	261	.0535	.311	.0760
.112	.0099	.162	.0206	.212	.0353	.262	.0539	.312	.0765
.113	.0100	.163	.0209	.213	.0356	.263	.0543	.313	.0769
.114	.0102	.164	.0211	.214	.0360	.264	.0547	.314	.0774
.115	.0104	.165	.0214	.215	.0363	.265	.0552	.315	.0779
.116	.0106	.166	.0216	.216	.0366	.266	.0556	.316	.0784
.117	.0108	.167	.0219	.217	.0370	.267	.0560	.317	.0789
.118	.0109	.168	.0222	.218	.0373	.268	.0564	.318	.0794
.119	.0111	.169	.0224	.219	.0377	.269	.0568	.319	.0799
.120	.0113	.170	.0227	.220	.0380	.270	.0573	.320	.0804
121	.0115	.171	.0230	.221	.0384	.271	.0577	.321	.0809
.122	.0117	.172	.0232	.222	.0387	.272	.0581	.322	.0814
.123	.0119	.173	.0235	.223	.0391	.273	.0585	.323	.0819
.124	.0121	.174	.0238	.224	.0394	.274	.0590	.324	.0824
.125	.0123	.175	.0241	.225	.0398	.275	.0594	.325	.0830
.126	.0125	.176	.0243	.226	.0401	.276	.0598	.326	.0835
.127	.0127	.177	.0246	.227	.0405	.277	.0603	.327	.0840
.128	.0129	.178	.0249	.228	.0408	.278	.0607	.328	.0845
.129	.0131	.179	.0252	.229	.0412	.279	.0611	.329	.0850
.130	.0133	.180	.0254	.230	.0415	.280	.0616	.330	.0855
.131	.0135	.181	.0257	.231	.0419	.281	.0620	.331	.0860
.132	.0137	.182	.0260	.232	.0423	.282	.0625	.332	.0866
.133	.0139	.183	.0263	.233	.0426	.283	.0629	.333	.0871
.134	.0141	.184	.0266	.234	.0430	.284	.0633	.334	.0876
.135	.0143	.185	.0269	.235	.0434	.285	.0638	.335	.0881
.136	.0145	.186	.0272	.236	.0437	.286	.0642	.336	.0887
.137	.0147	.187	.0275	.237	.0441	.287	.0647	.337	.0892
.138	.0150	.188	.0278	.238	.0445	.288	.0651	.338	.0897
.139	.0152	.189	.0281	.239	.0449	.289	.0656	.339	.0903
.140	.0154	.190	.0284	.240	.0452	.290	.0661	.340	.0908
.141	.0156	.191	.0287	.241	.0456	.291	.0665	.341	.0913
.142	.0158	.192	.0290	.242	.0460	.292	.0670	.342	.0919
.143	.0161	.193	.0293	.243	.0464	.293	.0674	.343	.0924
.144	.0163	.194	.0296	.244	.0468	.294	.0679	.344	.0929
.145	.0165	.195	.0299	.245	.0471	.295	.0683	.345	.0935
.146	.0167	.196	.0302	.246	.0475	.296	.0688	.346	.0940
.147	.0170	.197	.0305	.247	.0479	.297	.0693	.347	.0946
.148	.0172	.198	.0308	.248	.0483	.298	.0697	.348	.0951
.149	.0174	.199	.0311	.249	.0487	.299	.0702	.349	.0957
.150	.0177	.200	.0314	.250	.0491	.300	.0707	.350	.0962

TABLE OF CROSS-SECTIONAL AREAS FOR ROUND SPECIMENS—*Continued*

Dia.	Area	Dia.	Area	Dia.	Area	Dia.	Area	Dia.	Area
.351	.0968	.401	.1263	.451	.1598	.501	.1971	.551	.2384
.352	.0973	.402	.1269	.452	.1605	.502	.1979	.552	.2393
.353	.0979	.403	.1276	.453	.1612	.503	.1987	.553	.2402
.354	.0984	.404	.1282	.454	.1619	.504	.1995	.554	.2411
.355	.0990	.405	.1288	.455	.1626	.505	.2003	.555	.2419
.356	.0995	.406	.1295	.456	.1633	.506	.2011	.556	.2428
.357	.1001	.407	.1301	.457	.1640	.507	.2019	.557	.2437
.358	.1007	.408	.1307	.458	.1647	.508	.2027	.558	.2445
.359	.1012	.409	1314	.459	.1655	.509	.2035	.559	.2454
.360	.1018	.410	.1320	.460	.1662	.510	.2043	.560	.2463
.361	.1024	.411	.1327	.461	.1669	.511	.2051	.561	.2472
.362	.1029	.412	.1333	.462	.1676	.512	.2059	.562	.2481
.363	.1035	.413	.1340	.463	.1684	.513	.2067	.563	.2489
.364	.1041	.414	.1346	.464	.1691	.514	.2075	.564	.2498
.365	.1046	.415	.1353	.465	.1698	.515	.2083	.565	.2507
.366	.1052	.416	.1359	.466	.1706	.516	.2091	.566	.2516
.367	.1058	.417	.1366	.467	.1713	.517	.2099	.567	.2525
.368	.1064	.418	.1372	.468	.1720	.518	.2107	.568	.2534
.369	.1069	.419	.1379	.469	.1728	.519	.2116	.569	.2543
.370	.1075	.420	.1385	.470	.1735	.520	.2124	.570	.2552
.371	.1081	.421	.1392	.471	.1742	.521	.2132	.571	.2561
.372	.1087	.422	.1399	.472	.1750	.522	.2140	.572	.2570
.373	.1093	.423	.1405	.473	.1757	.523	.2148	.573	.2579
.374	.1099	.434	.1412	.474	.1765	.524	.2157	.574	.2588
.375	.1104	.425	.1419	.475	.1772	.525	.2165	.575	.2597
.376	.1110	.426	.1425	.476	.1780	.526	.2173	.576	.2606
.377	.1116	.427	.1432	.477	.1787	.527	.2181	.577	.2615
.378	.1122	.428	.1439	.478	.1795	.528	.2190	.578	.2624
.379	.1128	.429	.1445	.479	.1802	.529	.2198	.579	.2633
.380	.1134	.430	.1452	.480	.1810	.530	.2206	.580	.2642
.381	.1140	.431	1459	.481	.1817	.531	.2215	.581	.2651
.382	.1146	.432	.1466	.482	.1825	.532	.2223	.582	.2660
.383	.1152	.433	.1473	.483	.1832	.533	.2231	.583	.2669
.384	.1158	.434	.1479	.484	.1840	.534	.2240	.584	.2679
.385	.1164	.435	.1486	.485	.1847	.535	.2248	.585	.2688
.386	.1170	.436	.1493	.486	.1855	.536	.2256	.586	.2697
.387	.1176	.437	.1500	.487	.1863	.537	.2265	.587	.2706
.388	.1182	.438	.1507	.488	.1870	.538	.2273	.588	.2715
.389	.1188	.439	.1514	.489	.1878	.539	.2282	.589	.2725
.390	.1195	.440	.1521	.490	.1886	.540	.2290	.590	.2734
.391	.1201	.441	.1527	.491	.1893	.541	.2299	.591	.2743
.392	.1207	.442	.1534	.492	.1901	.542	.2307	.592	.2753
.393	.1213	.443	.1541	.493	.1909	.543	.2316	.593	.2762
.394	.1219	.444	.1548	.494	.1917	.544	.2324	.594	.2771
.395	.1225	.445	.1555	.495	.1924	.545	.2333	.595	.2781
.396	.1232	.446	.1562	.496	.1932	.546	.2341	.596	.2790
.397	.1238	.447	.1569	.497	.1940	.547	.2350	.597	.2799
.398	.1244	.448	.1576	.498	.1948	.548	.2359	.598	.2809
.399	.1250	.449	.1583	.499	.1956	.549	.2367	.599	.2818
.400	.1257	.450	.1590	.500	.1964	.550	.2376	.600	.2827

TABLE OF CROSS-SECTIONAL AREAS FOR ROUND SPECIMENS—*Continued*

Dia.	Area	Dia.	Area	Dia.	Area	Dia.	Area	Dia.	Area
.601	.2837	.651	.3329	.701	.3859	.751	.4430	.801	.5039
.602	.2846	.652	.3339	.702	.3870	.752	.4441	.802	.5052
.603	.2856	.653	.3349	.703	.3881	.753	.4453	.803	.5064
.604	.2865	.654	.3359	.704	.3893	.754	.4465	.804	.5077
.605	.2875	.655	.3370	.705	.3904	.755	.4477	.805	.5090
.606	.2884	.656	.3380	.706	.3915	.756	.4489	.806	.5102
.607	.2894	.657	.3390	.707	.3926	.757	.4501	.807	.5115
.608	.2903	.658	.3400	.708	.3937	.758	.4513	.808	.5128
.609	.2913	.659	.3411	.709	.3948	.759	.4525	.809	.5140
.610	.2922	.660	.3421	.710	.3959	.760	.4536	.810	.5153
.611	.2932	.661	.3432	.711	.3970	.761	.4548	.811	.5166
.612	.2942	.662	.3442	.712	.3981	.762	.4560	.812	.5178
.613	.2951	.663	.3452	.713	.3993	.763	.4572	.813	.5191
.614	.2961	.664	.3463	.714	.4004	.764	.4584	.814	.5204
.615	.2971	.665	.3473	.715	.4015	.765	.4596	.815	.5217
.616	.2980	.666	.3484	.716	.4026	.766	.4608	.816	.5230
.617	.2990	.667	.3494	.717	.4038	.767	.4620	.817	.5242
.618	.3000	.668	.3505	.718	.4049	.768	.4632	.818	.5255
.619	.3009	.669	.3515	.719	.4060	.769	.4645	.819	.5268
.620	.3019	.670	.3526	.720	.4072	.770	.4657	.820	.5281
.621	.3029	.671	.3536	.721	.4083	.771	.4669	.821	.5294
.622	.3039	.672	.3547	.722	.4094	.772	.4681	.822	.5307
.623	.3048	.673	.3557	.723	.4106	.773	.4693	.823	.5320
.624	.3058	.674	.3568	.724	.4117	.774	.4705	.824	.5333
.625	.3068	.675	.3578	.725	.4128	.775	.4717	.825	.5346
.626	.3078	.676	.3589	.726	.4140	.776	.4729	.826	.5359
.627	.3088	.677	.3600	.727	.4151	.777	.4742	.827	.5372
.628	.3097	.678	.3610	.728	.4162	.778	.4754	.828	.5385
.629	.3107	.679	.3621	.729	.4174	.779	.4766	.829	.5398
.630	.3117	.680	.3632	.730	.4185	.780	.4778	.830	.5411
.631	.3127	.681	.3642	.731	.4197	.781	.4791	.831	.5424
.632	.3137	.682	.3653	.732	.4208	.782	.4803	.832	.5437
.633	.3147	.683	.3664	.733	.4220	.783	.4815	.833	.5450
.634	.3157	.684	.3675	.734	.4231	.784	.4828	.834	.5463
.635	.3167	.685	.3685	.735	.4243	.785	.4840	.835	.5476
.636	.3177	.686	.3696	.736	.4254	.786	.4852	.836	.5489
.637	.3187	.687	.3707	.737	.4266	.787	.4865	.837	.5502
.638	.3197	.688	.3718	.738	.4278	.788	.4877	.838	.5515
.639	.3207	.689	.3728	.739	.4289	.789	.4889	.839	.5529
.640	.3217	.690	.3739	.740	.4301	.790	.4902	.840	.5542
.641	.3227	.691	.3750	.741	.4312	.791	.4914	.841	.5555
.642	.3237	.692	.3761	.742	.4324	.792	.4927	.842	.5568
.643	.3247	.693	.3772	.743	.4336	.793	.4939	.843	.5581
.644	.3257	.694	.3783	.744	.4347	.794	.4951	.844	.5595
.645	.3267	.695	.3794	.745	.4359	.795	.4964	.845	.5608
.646	.3278	.696	.3805	.746	.4371	.796	.4976	.846	.5621
.647	.3288	.697	.3816	.747	.4383	.797	.4989	.847	.5635
.648	.3298	.698	.3826	.748	.4394	.798	.5001	.848	.5648
.649	.3308	.699	.3837	.749	.4406	.799	.5014	.849	.5661
.650	.3318	.700	.3848	.750	.4418	.800	.5027	.850	.5675

TABLE OF CROSS-SECTIONAL AREAS FOR ROUND SPECIMENS—*Continued*

Dia.	Area	Dia.	Area	Dia.	Area	Dia.	Area	Dia.	Area
.851	.5688	.901	.6376	.951	.7103	1.001	.7870	1.051	.8675
.852	.5701	.902	.6390	.952	.7118	1.002	.7885	1.052	.8692
.853	.5715	.903	.6404	.953	.7133	1.003	.7901	1.053	.8708
.854	.5728	.904	.6418	.954	.7148	1.004	.7917	1.054	.8725
.855	.5741	.905	.6433	.955	.7163	1.005	.7933	1.055	.8742
.856	.5755	.906	.6447	.956	.7178	1.006	.7948	1.056	.8758
.857	.5768	.907	.6461	.957	.7193	1.007	.7964	1.057	.8775
.858	.5782	.908	.6475	.958	.7208	1.008	.7980	1.058	.8791
.859	.5795	.909	.6490	.959	.7223	1.009	.7996	1.059	.8808
.860	.5809	.910	.6504	.960	.7238	1.010	.8012	1.060	.8825
.861	.5822	.911	.6518	.961	.7253	1.011	.8028	1.061	.8841
.862	.5836	.912	.6533	.962	.7268	1.012	.8044	1.062	.8858
.863	.5849	.913	.6547	.963	.7284	1.013	.8059	1.063	.8875
.864	.5863	.914	.6561	.964	.7299	1.014	.8075	1.064	.8891
.865	.5877	.915	.6576	.965	.7314	1.015	.8091	1.065	.8908
.866	.5890	.916	.6590	.966	.7329	1.016	.8107	1.066	.8925
.867	.5904	.917	.6604	.967	.7344	1.017	.8123	1.067	.8942
.868	.5917	.918	.6619	.968	.7359	1.018	.8139	1.068	.8958
.869	.5931	.919	.6633	.969	.7375	1.019	.8155	1.069	.8975
.870	.5945	.920	.6648	.970	.7390	1.020	.8171	1.070	.8992
.871	.5958	.921	.6662	.971	.7405	1.021	.8187	1.071	.9009
.872	.5972	.922	.6677	.972	.7420	1.022	.8203	1.072	.9026
.873	.5986	.923	.6691	.973	.7436	1.023	.8219	1.073	.9042
.874	.5999	.924	.6706	.974	.7451	1.024	.8235	1.074	.9059
.875	.6013	.925	.6720	.975	.7466	1.025	.8252	1.075	.9076
.876	.6027	.926	.6735	.976	.7482	1.026	.8268	1.076	.9093
.877	.6041	.927	.6749	.977	.7497	1.027	.8284	1.077	.9110
.878	.6055	.928	.6764	.978	.7512	1.028	.8300	1.078	.9127
.879	.6068	.929	.6778	.979	.7528	1.029	.8316	1.079	.9144
.880	.6082	.930	.6793	.980	.7543	1.030	.8332	1.080	.9161
.881	.6096	.931	.6808	.981	.7558	1.031	.8348	1.081	.9178
.882	.6110	.932	.6822	.982	.7574	1.032	.8365	1.082	.9195
.883	.6124	.933	.6837	.983	.7589	1.033	.8381	1.083	.9212
.884	.6138	.934	.6851	.984	.7605	1.034	.8397	1.084	.9229
.885	.6151	.935	.6866	.985	.7620	1.035	.8413	1.085	.9246
.886	.6165	.936	.6881	.986	.7636	1.036	.8430	1.086	.9263
.887	.6179	.937	.6896	.987	.7651	1.037	.8446	1.087	.9280
.888	.6193	.938	.6910	.988	.7667	1.038	.8462	1.088	.9297
.889	.6207	.939	.6925	.989	.7682	1.039	.8478	1.089	.9314
.890	.6221	.940	.6940	.990	.7698	1.040	.8495	1.090	.9331
.891	.6235	.941	.6955	.991	.7713	1.041	.8511	1.091	.9348
.892	.6249	.942	.6969	.992	.7729	1.042	.8527	1.092	.9365
.893	.6263	.943	.6984	.993	.7744	1.043	.8544	1.093	.9383
.894	.6277	.944	.6999	.994	.7760	1.044	.8560	1.094	.9400
.895	.6291	.945	.7014	.995	.7776	1.045	.8577	1.095	.9417
.896	.6305	.946	.7029	.996	.7791	1.046	.8593	1.096	.9434
.897	.6319	.947	.7044	.997	.7807	1.047	.8610	1.097	.9451
.898	.6333	.948	.7058	.998	.7823	1.048	.8626	1.098	.9469
.899	.6348	.949	.7073	.999	.7838	1.049	.8642	1.098	.9486
.900	.6362	.950	.7088	1.000	.7854	1.050	.8659	1.100	.9503

.250

PERCENTAGE REDUCTION OF AREA TABLES

Original Diameter, Inches

Final Diameter, Inches

	.240	.241	.242	.243	.244	.245	.246	.247	.248	.249	.250	.251	.252	.253	.254	.255	.256	.257	.258	.259	.260
.135	68.4	68.6	69.0	69.3	69.5	69.7	70.0	70.3	70.5	70.6	70.7	71.1	71.4	71.6	71.6	71.9	72.3	72.5	72.6	72.9	73.0
.136	68.0	68.2	68.5	69.0	69.1	69.3	69.5	69.7	69.9	70.1	70.4	70.8	71.0	71.1	71.3	71.5	72.0	72.0	72.3	72.4	72.6
.138	67.0	67.3	67.6	68.0	68.2	68.3	68.5	68.7	69.0	69.3	69.5	69.8	70.0	70.4	70.5	70.6	71.0	71.3	71.5	71.6	71.8
.140	66.0	66.3	66.6	67.0	67.1	67.4	67.5	67.9	68.2	68.5	68.6	69.0	69.2	69.5	69.6	69.9	70.3	70.5	70.6	70.7	71.0
.142	65.0	65.3	65.6	66.0	66.1	66.4	66.6	67.1	67.4	67.5	67.8	68.2	68.4	68.5	68.8	69.0	69.4	69.6	69.8	70.0	70.2
.144	64.0	64.3	64.6	65.0	65.1	65.3	65.6	66.2	66.5	66.6	66.9	67.1	67.3	67.5	67.7	68.0	68.5	68.6	68.8	69.0	69.2
.146	63.0	63.3	63.6	64.0	64.2	64.5	64.7	65.1	65.4	65.6	65.9	66.2	66.5	66.7	67.0	67.1	67.5	67.8	68.0	68.1	68.4
.148	62.0	62.3	62.6	63.0	63.2	63.5	63.7	64.2	64.5	64.7	65.0	65.4	65.6	65.9	66.0	66.4	66.8	67.0	67.2	67.4	67.6
.150	60.8	61.3	61.7	62.0	62.3	62.5	62.9	63.3	63.5	63.8	64.0	64.5	64.6	64.9	65.2	65.5	65.8	66.0	66.4	66.5	66.7
.152	59.9	60.3	60.7	61.0	61.4	61.4	61.8	62.1	62.5	62.8	63.0	63.5	63.6	63.9	64.3	64.5	64.9	65.1	65.4	65.5	65.7
.154	58.8	59.3	59.6	60.0	60.2	60.4	60.8	61.1	61.5	61.8	62.0	62.5	62.8	62.9	63.4	63.5	63.9	64.2	64.5	64.6	64.9
.156	57.7	58.2	58.6	59.0	59.3	59.4	59.8	60.1	60.5	60.6	61.0	61.4	61.7	61.9	62.3	62.5	62.9	63.1	63.4	63.9	64.0
.158	56.6	57.0	57.5	57.9	58.1	58.4	58.8	59.1	59.5	59.8	60.0	60.5	60.7	61.0	61.3	61.6	62.0	62.3	62.5	62.8	63.1
.160	55.5	56.0	56.4	56.8	57.1	57.3	57.7	58.0	58.5	58.6	59.0	59.4	59.7	59.9	60.3	60.5	61.0	61.3	61.5	61.8	62.0
.162	54.4	54.9	55.3	55.7	56.0	56.2	56.7	57.0	57.4	57.8	58.0	58.5	58.8	59.0	59.3	59.6	60.0	60.4	60.6	60.9	61.2
.164	53.3	53.8	54.1	54.6	55.0	55.2	55.6	56.0	56.3	56.6	56.9	57.4	57.7	58.0	58.3	58.6	59.0	59.4	59.6	59.9	60.1
.166	52.2	52.5	53.0	53.5	53.8	54.0	54.5	55.0	55.3	55.5	55.9	56.5	56.7	57.0	57.3	57.6	58.1	58.4	58.7	59.0	59.3
.168	51.0	51.4	51.9	52.8	52.6	53.0	53.4	53.8	54.1	54.4	54.8	55.3	55.6	56.0	56.3	56.6	57.0	57.4	57.6	58.0	58.2
.170	49.8	50.3	50.8	51.2	51.5	51.9	52.4	52.7	53.1	53.3	53.7	54.4	54.5	55.0	55.2	55.5	56.2	56.4	56.7	57.0	57.2
.172	48.7	49.0	49.6	50.0	50.4	50.8	51.4	51.6	52.0	52.2	52.6	53.2	53.5	53.9	54.2	54.5	55.0	55.4	55.6	56.0	56.4
.174	47.5	47.9	48.4	48.9	49.2	49.6	50.0	50.4	50.8	51.1	51.5	52.0	52.4	52.9	53.1	53.5	54.0	54.3	54.6	54.9	55.2
.176	46.3	46.8	47.2	47.6	48.0	48.4	48.9	49.2	49.6	50.0	50.4	50.7	51.3	51.8	52.0	52.4	52.8	53.2	53.5	53.8	54.0
.178	45.1	45.4	46.0	46.4	46.9	47.2	47.8	48.1	48.5	48.9	49.3	49.8	50.2	50.5	51.0	51.3	51.9	52.1	52.5	52.9	53.1
.180	43.8	44.2	44.8	45.2	45.6	46.0	46.5	47.0	47.4	47.8	48.1	48.7	49.0	49.4	49.8	50.2	50.7	51.0	51.4	51.8	52.1
.182	42.5	43.0	43.5	44.0	44.4	44.8	45.3	45.8	46.2	46.6	47.0	47.6	48.0	48.3	48.7	49.2	49.6	49.9	50.3	50.7	51.0
.184	41.2	41.7	42.3	42.7	43.2	43.6	44.0	44.8	45.0	45.4	45.8	46.4	46.8	47.2	47.6	48.0	48.4	48.9	49.3	49.6	49.9
.186	39.9	40.4	41.0	41.5	42.0	42.4	42.8	43.5	43.8	44.2	44.6	45.2	45.6	45.9	46.5	46.8	47.3	47.7	48.1	48.5	48.8
.188	38.6	39.2	39.7	40.2	40.7	41.1	41.6	42.1	42.6	43.0	43.4	44.0	44.4	44.8	45.3	45.7	46.2	46.6	46.9	47.4	47.7
.190	37.3	37.8	38.4	39.0	39.5	39.9	40.4	40.9	41.4	41.3	42.2	42.8	43.2	43.6	44.1	44.5	45.0	45.4	45.8	46.2	46.5
.192	36.0	36.5	37.1	37.6	38.2	38.6	39.1	39.6	40.1	40.5	41.0	41.6	42.0	42.4	42.9	43.4	43.8	44.3	44.6	45.0	45.4
.194	34.6	35.2	35.8	36.3	36.8	37.3	37.9	38.4	38.9	39.3	39.8	40.4	40.8	41.2	41.7	42.2	42.6	43.1	43.5	43.9	44.3
.196	33.3	33.8	34.5	35.0	35.5	36.0	36.6	37.1	37.6	38.0	38.6	39.1	39.6	40.0	40.5	41.0	41.5	41.9	42.4	42.7	43.2
.198	32.0	32.5	33.2	33.6	34.2	34.7	35.2	35.8	36.3	36.7	37.3	37.8	38.3	38.8	39.3	39.7	40.2	40.7	41.2	41.6	42.0
.200	30.6	31.1	31.8	32.3	32.9	33.4	34.0	34.5	35.0	35.4	36.0	36.6	37.1	37.6	38.1	38.5	39.0	39.6	39.9	40.4	40.8
.202	29.2	29.8	30.2	31.0	31.5	32.0	32.6	33.2	33.7	34.2	34.7	35.3	35.8	36.3	36.8	37.3	37.8	38.3	38.7	39.2	39.6
.204	27.8	28.4	29.0	29.6	30.1	30.4	31.3	31.8	32.4	32.9	33.4	34.0	34.6	35.0	35.5	36.0	36.6	37.0	37.6	38.0	38.5
.206	26.4	26.9	27.6	28.2	28.8	29.2	29.9	30.4	31.0	31.5	32.1	32.7	33.3	33.7	34.2	34.8	35.3	35.8	36.3	36.8	37.2
.208	24.9	25.5	26.2	26.8	27.4	27.9	28.6	29.2	29.7	30.2	30.8	31.4	31.9	32.4	32.9	33.5	34.0	34.6	35.0	35.6	36.0
.210	23.5	24.0	24.8	25.3	26.0	26.5	27.2	27.8	28.4	28.8	29.4	30.1	30.6	31.1	31.7	32.2	32.7	33.3	33.8	34.3	34.8
.212	22.0	22.7	23.3	23.9	24.5	25.2	25.8	26.4	27.0	27.6	28.2	28.7	29.3	29.8	30.3	30.8	31.4	32.0	32.5	33.0	33.6
.214	20.5	21.2	21.8	22.5	23.0	23.6	24.3	25.0	25.6	26.2	27.2	27.4	28.0	28.5	29.0	29.6	30.2	30.7	31.3	31.7	32.3
.216	19.0	19.7	20.3	21.0	21.6	22.4	23.0	23.7	24.4	24.9	25.6	26.2	26.8	27.4	27.8	28.4	29.0	29.6	30.1	30.6	31.2
.218	17.5	18.2	18.9	19.6	20.2	20.8	21.5	22.1	22.8	23.4	24.2	24.6	25.2	25.8	26.3	27.0	27.6	28.1	28.6	29.4	29.7
.220	16.0	16.7	17.4	18.1	18.7	19.4	20.0	20.5	21.4	21.9	22.6	23.2	23.8	24.4	25.0	25.4	26.2	26.8	27.3	27.9	28.4
.222	14.4	15.1	15.8	16.6	17.2	17.9	18.5	19.2	19.9	20.5	21.1	21.8	22.3	23.0	23.6	24.2	24.8	25.4	26.0	26.7	27.0
.224	12.9	13.6	14.3	15.1	15.7	16.4	17.1	17.8	18.4	19.1	19.7	20.4	21.0	21.6	22.2	22.8	23.5	24.0	24.6	25.4	25.8
.226	11.3	12.1	12.6	13.5	14.2	14.9	15.6	16.3	17.0	17.6	18.4	19.0	19.6	20.2	20.8	21.4	22.0	22.7	23.2	23.8	24.5
.228	9.3	10.5	11.2	12.0	12.7	13.4	14.1	14.8	15.5	16.2	16.9	17.5	18.2	18.8	19.4	20.0	20.7	21.3	21.9	22.5	23.0
.230	8.2	8.9	9.7	10.4	11.1	11.9	12.6	13.3	14.0	14.7	15.4	16.0	16.7	17.4	18.0	18.6	19.3	19.9	20.6	21.2	21.8
.232	6.4	7.4	8.1	8.8	9.6	10.3	11.1	11.8	12.5	13.2	13.9	14.6	15.2	15.9	16.6	17.2	17.9	18.5	19.2	19.8	20.4
.234	4.9	5.7	6.5	7.2	8.0	8.8	9.5	10.3	11.0	11.7	12.4	13.1	13.8	14.4	15.1	15.8	16.6	17.1	17.7	18.4	19.0
.236	3.3	4.1	4.9	5.7	6.5	7.2	8.0	8.7	9.5	10.2	11.0	11.6	12.3	13.0	13.7	14.3	15.0	15.7	16.3	17.0	17.7
.238	1.6	2.5	3.3	4.1	4.9	5.6	6.4	7.1	7.9	8.6	9.4	10.1	10.8	11.5	12.2	12.9	13.6	14.2	14.9	15.6	16.2
.240	...	0.8	1.6	2.5	3.3	4.0	4.8	5.6	6.4	7.1	7.9	8.6	9.3	10.0	10.7	11.4	12.1	12.8	13.5	14.1	14.9
.242	...	...	...	0.8	1.6	2.4	3.2	4.0	4.8	5.3	6.1	6.8	7.6	8.3	9.0	9.7	10.4	11.1	11.8	12.5	13.2
.244	...	...	...	...	...	0.8	1.6	2.4	3.2	4.0	4.7	5.5	6.3	7.0	7.7	8.4	9.2	9.9	10.6	11.3	11.9
.246	...	...	...	...	...	...	...	0.8	1.6	2.4	3.2	4.0	4.7	5.4	6.2	6.9	7.7	8.4	9.1	9.9	10.6

PERCENTAGE REDUCTION OF AREA TABLES

Original Diameter, Inches

Final Diameter, Inches

	.365	.366	.367	.368	.369	.370	.371	.372	.373	.374	.375	.376	.377	.378	.379	.380	.381	.382	.383	.384	.385
.226	61.8	61.9	62.1	62.2	62.5	62.7	62.9	63.1	63.3	63.5	63.6	63.8	64.0	64.3	64.5	64.6	64.8	65.0	65.2	65.4	65.6
.228	61.0	61.2	61.5	61.6	61.9	62.1	62.2	62.5	62.6	62.9	63.0	63.2	63.4	63.6	63.8	64.0	64.2	64.4	64.5	64.8	64.9
.230	60.3	60.5	60.8	61.0	61.2	61.4	61.6	61.9	62.0	62.3	62.4	62.6	62.9	63.0	63.2	63.4	63.6	63.9	64.0	64.2	64.3
.232	59.6	59.7	60.1	60.3	60.5	60.7	60.8	61.1	61.2	61.5	61.7	62.0	62.2	62.3	62.5	62.7	62.9	63.1	63.2	63.5	63.7
.234	59.0	59.1	59.4	59.5	59.8	60.0	60.2	60.6	60.7	60.8	61.0	61.2	61.5	61.6	61.9	62.1	62.3	62.5	62.6	62.9	63.0
.236	58.2	58.4	58.7	58.9	59.2	59.3	59.5	59.8	60.0	60.1	60.3	60.6	60.8	61.0	61.3	61.5	61.7	61.9	62.0	62.4	62.5
.238	57.5	57.7	58.0	58.2	58.4	58.6	58.8	59.1	59.2	59.5	59.6	59.9	60.2	60.3	60.5	60.7	61.0	61.3	61.4	61.6	61.8
.240	56.8	57.0	57.4	57.5	57.8	58.0	58.1	58.5	58.6	58.8	59.0	59.3	59.5	59.7	60.0	60.2	60.4	60.6	60.7	61.0	61.2
.242	56.1	56.2	56.6	56.8	57.0	57.2	57.4	57.8	57.9	58.1	58.3	58.6	58.9	59.0	59.2	59.4	59.6	59.9	60.0	60.3	60.5
.244	55.3	55.5	55.9	56.0	56.3	56.5	56.7	57.0	57.1	57.4	57.6	57.9	58.1	58.2	58.5	58.7	59.0	59.2	59.3	59.6	59.8
.246	54.7	54.8	55.2	55.3	55.6	55.8	56.0	56.3	56.5	56.7	56.9	57.2	57.5	57.6	57.9	58.1	58.3	58.6	58.7	59.0	59.2
.248	53.8	54.1	54.4	54.6	54.9	55.1	55.3	55.6	55.8	56.0	56.2	56.5	56.8	56.9	57.2	57.4	57.6	57.9	58.0	58.3	58.5
.250	53.1	53.3	53.7	53.9	54.1	54.3	54.5	54.9	55.0	55.3	55.5	55.8	56.0	56.2	56.5	56.7	57.0	57.2	57.3	57.6	57.8
.252	52.4	52.5	52.9	53.1	53.4	53.6	53.8	54.1	54.3	54.5	54.8	55.1	55.4	55.5	55.8	56.0	56.2	56.5	56.7	56.9	57.1
.254	51.5	51.8	52.2	52.4	52.7	52.9	53.1	53.4	53.6	53.9	54.1	54.3	54.6	54.7	55.0	55.2	55.5	55.8	56.0	56.2	56.5
.256	50.8	51.0	51.4	51.6	51.9	52.1	52.3	52.7	52.9	53.1	53.3	53.6	53.9	54.0	54.4	54.6	54.8	55.1	55.3	55.5	55.8
.258	50.0	50.2	50.6	50.8	51.1	51.3	51.6	51.9	52.1	52.5	52.7	52.9	53.2	53.3	53.6	53.8	54.1	54.4	54.6	54.9	55.1
.260	49.3	49.5	49.9	50.1	50.3	50.6	50.8	51.2	51.4	51.7	51.9	52.1	52.5	52.6	53.0	53.2	53.4	53.8	53.9	54.2	54.4
.262	48.5	48.7	49.1	49.3	49.6	49.8	50.1	50.4	50.6	51.0	51.2	51.5	51.8	51.9	52.2	52.4	52.7	53.0	53.1	53.5	53.7
.264	47.8	48.0	48.4	48.5	48.9	49.1	49.3	49.7	49.9	50.2	50.4	50.7	51.0	51.2	51.6	51.8	52.0	52.3	52.5	52.9	53.0
.266	46.9	47.1	47.5	47.7	48.0	48.2	48.5	48.9	49.1	49.3	49.6	49.9	50.2	50.4	50.7	50.9	51.2	51.5	51.7	52.0	52.2
.268	46.0	46.3	46.7	47.0	47.3	47.5	47.8	48.1	48.3	48.7	48.9	49.2	49.5	49.7	50.0	50.2	50.5	50.9	51.0	51.3	51.5
.270	45.3	45.5	45.9	46.1	46.4	46.6	46.9	47.3	47.5	47.9	48.1	48.4	48.7	48.9	49.2	49.5	49.7	50.0	50.2	50.5	50.8
.272	44.4	44.7	45.1	45.3	45.7	45.9	46.2	46.6	46.8	47.1	47.3	47.6	48.0	48.2	48.5	48.8	49.0	49.3	49.5	49.9	50.1
.274	43.6	43.8	44.3	44.5	44.9	45.1	45.4	45.8	46.0	46.4	46.5	46.8	47.2	47.4	47.7	47.9	48.2	48.6	48.8	49.1	49.3
.276	42.9	43.1	43.5	43.8	44.1	44.4	44.6	45.0	45.2	45.6	45.8	46.1	46.4	46.6	47.0	47.3	47.5	47.8	48.0	48.4	48.6
.278	42.0	42.2	42.7	42.9	43.3	43.6	43.8	44.2	44.4	44.8	45.0	45.3	45.6	45.8	46.3	46.6	46.8	47.1	47.3	47.7	47.9
.280	41.2	41.4	41.8	42.1	42.4	42.7	43.0	43.4	43.6	44.0	44.2	44.5	44.8	45.0	45.5	45.7	46.0	46.3	46.5	46.9	47.1
.282	40.3	40.5	41.0	41.2	41.6	41.8	42.1	42.5	42.8	43.1	43.3	43.7	44.0	44.2	44.6	44.9	45.2	45.5	45.7	46.1	46.3
.284	39.6	39.8	40.2	40.5	40.8	41.1	41.4	41.8	42.0	42.4	42.6	43.0	43.3	43.5	43.9	44.2	44.5	44.8	45.0	45.4	45.6
.286	38.6	38.9	39.3	39.6	40.0	40.3	40.5	41.0	41.2	41.6	41.8	42.2	42.5	42.7	43.1	43.4	43.7	44.0	44.2	44.6	44.8
.288	37.8	38.1	38.5	38.8	39.1	39.4	39.7	40.1	40.4	40.8	41.0	41.4	41.7	41.9	42.3	42.6	42.9	43.2	43.4	43.8	44.0
.290	36.8	37.1	37.5	37.8	38.2	38.5	38.8	39.2	39.4	39.9	40.1	40.4	40.8	41.0	41.4	41.7	42.0	42.3	42.6	43.0	43.2
.292	36.0	36.3	36.7	37.0	37.4	37.7	38.0	38.4	38.6	39.0	39.2	39.6	40.0	40.3	40.6	40.9	41.2	41.6	41.9	42.2	42.4
.294	35.1	35.4	35.8	36.2	36.6	36.8	37.2	37.6	37.8	38.2	38.5	38.8	39.2	39.4	39.8	40.1	40.4	40.8	41.0	41.4	41.6
.296	34.2	34.5	35.0	35.3	35.7	36.0	36.3	36.7	37.0	37.4	37.6	38.0	38.4	38.6	39.0	39.3	39.6	40.0	40.2	40.6	40.9
.298	33.4	33.7	34.1	34.4	34.8	35.1	35.5	35.9	36.2	36.6	36.8	37.2	37.6	37.8	38.2	38.6	38.9	39.2	39.5	39.8	40.1
.300	32.4	32.7	33.2	33.5	33.9	34.2	34.6	35.0	35.3	35.6	35.9	36.3	36.7	36.9	37.4	37.7	38.0	38.3	38.6	39.0	39.2
.302	31.6	31.9	32.4	32.7	33.1	33.4	33.8	34.2	34.5	34.8	35.1	35.5	35.9	36.2	36.6	36.9	37.2	37.5	37.8	38.2	38.4
.304	30.6	30.9	31.4	31.7	32.1	32.4	32.8	33.2	33.5	33.9	34.2	34.6	34.9	35.3	35.7	36.0	36.3	36.7	36.9	37.3	37.6
.306	29.8	30.1	30.6	30.9	31.3	31.6	32.0	32.4	32.7	33.1	33.4	33.8	34.2	34.4	34.8	35.1	35.4	35.8	36.2	36.6	36.8
.308	28.8	29.2	29.6	30.0	30.4	30.7	31.1	31.5	31.8	32.2	32.5	32.9	33.3	33.6	34.0	34.3	34.6	35.0	35.3	35.7	35.9
.310	27.8	28.2	28.6	29.0	29.4	29.7	30.1	30.6	30.9	31.3	31.6	32.0	32.4	32.6	33.1	33.4	33.8	34.1	34.4	34.8	35.1
.312	26.9	27.2	27.7	28.1	28.5	28.8	29.2	29.6	30.0	30.4	30.7	31.1	31.5	31.8	32.2	32.5	32.9	33.2	33.6	34.0	34.2
.314	26.0	26.4	26.8	27.2	27.6	28.0	28.4	28.8	29.1	29.6	29.8	30.3	30.6	30.9	31.4	31.7	32.1	32.4	32.8	33.2	33.5
.316	25.1	25.4	25.9	26.3	26.7	27.1	27.4	27.9	28.2	28.7	28.9	29.4	29.8	30.1	30.5	30.8	31.2	31.6	31.9	32.3	32.6
.318	24.1	24.5	25.0	25.4	25.8	26.1	26.5	27.0	27.3	27.8	28.0	28.5	28.9	29.2	29.6	30.0	30.4	30.8	31.1	31.4	31.8
.320	23.2	23.6	24.0	24.4	24.8	25.2	25.6	26.1	26.4	26.8	27.1	27.6	28.0	28.3	28.7	29.1	29.5	29.8	30.2	30.6	30.9
.322	22.2	22.6	23.1	23.4	23.9	24.3	24.7	25.1	25.5	25.9	26.2	26.6	27.1	27.4	27.8	28.2	28.6	28.9	29.3	29.7	30.0
.324	21.2	21.6	22.1	22.5	23.0	23.3	23.8	24.2	24.6	25.0	25.3	25.8	26.2	26.5	26.9	27.3	27.7	28.1	28.4	28.8	29.2
.326	20.2	20.6	21.1	21.5	21.9	22.3	22.7	23.2	23.6	24.0	24.3	24.8	25.2	25.5	26.0	26.4	26.8	27.2	27.5	27.9	28.2
.328	19.3	19.7	20.2	20.6	21.0	21.4	21.8	22.3	22.7	23.1	23.4	23.9	24.3	24.6	25.1	25.5	25.9	26.3	26.6	27.0	27.4
.330	18.3	18.7	19.2	19.6	20.1	20.5	20.9	21.4	21.8	22.2	22.5	23.0	23.4	23.7	24.2	24.6	25.0	25.4	25.8	26.2	26.5
.332	17.2	17.7	18.2	18.6	19.1	19.4	19.8	20.4	20.8	21.2	21.5	21.9	22.4	22.8	23.2	23.6	24.0	24.4	24.8	25.2	25.6
.334	16.3	16.7	17.2	17.6	18.1	18.5	18.9	19.4	19.8	20.3	20.6	21.1	21.5	21.9	22.4	22.8	23.2	23.6	23.9	24.4	24.7
.336	15.3	15.7	16.2	16.6	17.1	17.5	17.9	18.4	18.8	19.3	19.6	20.1	20.5	20.9	21.4	21.8	22.2	22.6	23.0	23.4	23.8
.338	14.3	14.7	15.2	15.6	16.2	16.6	17.0	17.5	17.9	18.4	18.7	19.2	19.6	20.0	20.5	20.9	21.3	21.7	22.1	22.6	22.9
.340	13.2	13.7	14.2	14.6	15.1	15.5	16.0	16.5	16.9	17.4	17.7	18.2	18.6	19.0	19.5	19.9	20.4	20.8	21.2	21.6	22.0
.342	12.1	12.6	13.1	13.6	14.1	14.5	15.0	15.5	15.9	16.4	16.7	17.2	17.6	18.1	18.5	18.9	19.4	19.8	20.2	20.6	21.0
.344	11.2	11.7	12.2	12.7	13.2	13.6	14.0	14.5	15.0	15.5	15.8	16.3	16.8	17.2	17.7	18.1	18.5	18.9	19.3	19.8	20.2
.346	10.1	10.6	11.2	11.6	12.1	12.5	13.0	13.5	14.0	14.5	14.8	15.3	15.8	16.2	16.7	17.1	17.5	18.0	18.4	18.8	19.2
.348	9.1	9.6	10.1	10.6	11.1	11.5	12.0	12.5	13.0	13.5	13.8	14.3	14.8	15.2	15.7	16.2	16.6	17.0	17.4	17.9	18.3
.350	8.0	8.5	9.1	9.6	10.1	10.5	11.0	11.5	12.0	12.5	12.8	13.3	13.8	14.2	14.7	15.2	15.6	16.1	16.5	16.9	17.3
.352	7.0	7.5	8.0	8.5	9.1	9.5	10.0	10.5	11.0	11.5	11.8	12.3	12.8	13.3	13.7	14.2	14.6	15.1	15.5	16.0	16.4
.354	5.9	6.4	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	10.8	11.3	11.8	12.3	12.8	13.2	13.7	14.1	14.6	15.0	15.5
.356	4.8	5.4	6.0	6.5	7.0	7.4	8.0	8.5	9.0	9.5	9.9	10.3	10.8	11.3	11.8	12.3	12.7	13.2	13.6	14.1	14.5
.358	3.7	4.3	4.8	5.3	5.9	6.3	6.8	7.3	7.8	8.4	8.8	9.3	9.8	10.2	10.7	11.2	11.7	12.1	12.6	13.1	13.5
.360	2.7	3.2	3.8	4.3	4.9	5.3	5.8	6.3	6.8	7.4	7.8	8.3	8.8	9.3	9.8	10.3	10.7	11.2	11.6	12.1	12.5
.362	1.6	2.2	2.7	3.3	3.8	4.3	4.8	5.3	5.8	6.4	6.8	7.3	7.8	8.3	8.8	9.3	9.7	10.2	10.7	11.1	11.6
.364	0.5	1.0	1.6	2.2	2.7	3.2	3.7	4.2	4.8	5.3	5.7	6.2	6.7	7.2	7.7	8.2	8.7	9.2	9.6	10.1	10.6
.366	...	...	0.6	1.1	1.7	2.1	2.7	3.2	3.8	4.3	4.7	5.2	5.7	6.2	6.7	7.2	7.7	8.2	8.7	9.2	9.6

.505

PERCENTAGE REDUCTION OF AREA TABLES

Original Diameter, Inches

Final Diameter, Inches

	.495	.496	.497	.498	.499	.500	.501	.502	.503	.504	.505	.506	.507	.508	.509	.510	.511	.512	.513	.514	.515
.300	63.2	63.5	63.6	63.8	63.9	64.0	64.1	64.4	64.5	64.5	64.7	64.9	65.1	65.2	65.2	65.3	65.6	65.9	65.9	66.0	66.0
.302	62.8	63.0	63.1	63.4	63.4	63.5	63.6	64.0	64.0	64.0	64.2	64.5	64.7	64.6	64.8	64.8	65.1	65.5	65.5	65.5	65.5
.304	62.2	62.4	62.6	62.9	63.0	63.0	63.1	63.5	63.5	63.5	63.8	64.0	64.3	64.1	64.4	64.3	64.6	65.0	65.0	65.0	65.0
.306	61.7	61.9	62.1	62.4	62.5	62.5	63.6	63.0	63.0	63.1	63.3	63.5	63.8	63.6	64.0	63.8	64.2	64.5	64.5	64.5	64.6
.308	61.2	61.4	61.6	61.9	62.0	62.0	62.1	62.5	62.5	62.6	62.8	63.0	63.3	63.2	63.5	63.4	63.7	64.0	64.0	64.0	64.1
.310	60.7	60.9	61.1	61.4	61.5	61.5	61.6	62.0	62.0	62.1	62.3	62.5	62.8	62.8	63.0	63.0	63.2	63.5	63.5	63.6	63.6
.312	60.2	60.4	60.6	60.9	61.0	61.0	61.1	61.5	61.6	61.6	61.8	62.0	62.3	62.3	62.5	62.5	62.7	63.0	63.0	63.1	63.2
.314	59.8	60.0	60.1	60.4	60.5	60.5	60.6	61.0	61.1	61.2	61.4	61.5	61.8	61.9	62.0	62.0	62.2	62.5	62.5	62.7	62.8
.316	59.3	59.4	59.5	59.8	60.0	60.0	60.1	60.4	60.6	60.7	60.9	61.0	61.3	61.4	61.5	61.5	61.8	62.0	62.0	62.3	62.3
.318	58.8	58.9	59.0	59.3	59.5	59.5	59.6	59.9	60.1	60.2	60.4	60.5	60.8	60.9	61.0	61.0	61.3	61.5	61.6	61.8	61.8
.320	58.3	58.4	58.5	58.8	59.0	59.0	59.1	59.4	59.6	59.8	60.0	60.0	60.3	60.3	60.5	60.5	60.8	61.0	61.1	61.3	61.3
.322	57.8	57.9	58.0	58.3	58.5	58.5	58.6	58.9	59.1	59.3	59.4	59.5	59.8	59.8	60.0	60.0	60.3	60.5	60.6	60.8	60.8
.324	57.3	57.4	57.5	57.8	58.0	58.0	58.1	58.4	58.6	58.8	58.9	59.0	59.3	59.4	59.5	59.5	59.8	60.0	60.1	60.3	60.3
.326	56.5	56.7	57.0	57.3	57.5	57.5	57.6	57.9	58.1	58.1	58.3	58.5	58.8	58.8	59.0	59.0	59.3	59.5	59.5	59.7	59.8
.328	56.0	56.1	56.5	56.8	57.0	57.0	57.1	57.4	57.6	57.6	57.8	58.0	58.3	58.3	58.5	58.5	58.8	59.0	59.1	59.3	59.3
.330	55.5	55.6	56.0	56.2	56.4	56.4	56.6	56.9	57.1	57.2	57.4	57.5	57.8	57.8	58.0	58.0	58.4	58.5	58.6	58.8	58.8
.332	55.0	55.1	55.5	55.6	55.8	55.9	56.0	56.4	56.5	56.5	56.8	57.0	57.3	57.2	57.5	57.5	57.8	58.0	58.0	58.3	58.3
.334	54.4	54.6	55.0	55.1	55.2	55.4	55.5	55.8	56.0	56.0	56.2	56.5	56.8	56.7	57.0	57.0	57.4	57.5	57.6	57.8	57.9
.336	53.8	54.1	54.4	54.5	54.6	54.9	55.0	55.3	55.4	55.5	55.7	55.9	56.2	56.2	56.4	56.5	56.9	57.0	57.1	57.2	57.4
.338	53.2	53.5	53.8	54.0	54.1	54.3	54.5	54.8	54.9	55.0	55.2	55.5	55.8	55.7	55.9	56.0	56.4	56.5	56.6	56.7	56.9
.340	52.7	53.0	53.2	53.5	53.5	53.7	54.0	54.2	54.4	54.5	54.8	54.9	55.1	55.2	55.4	55.5	55.9	56.0	56.0	56.2	56.4
.342	52.2	52.5	52.6	52.9	53.0	53.2	53.5	53.6	53.7	54.0	54.2	54.4	54.6	54.5	54.9	55.0	55.4	55.4	55.5	55.7	55.9
.344	51.7	52.0	52.1	52.3	52.5	52.7	53.0	53.1	53.2	53.5	53.7	54.0	54.1	54.0	54.4	54.5	54.9	55.0	55.0	55.2	55.4
.346	51.1	51.4	51.5	51.7	52.0	52.2	52.4	52.5	52.6	53.0	53.2	53.4	53.5	53.5	53.9	53.9	54.3	54.4	54.5	54.7	55.0
.348	50.6	50.7	51.0	51.1	51.4	51.6	51.8	51.9	52.1	52.4	52.6	52.8	53.0	53.0	53.3	53.4	53.7	53.8	53.9	54.2	54.4
.350	50.0	50.1	50.4	50.6	50.8	51.0	51.2	51.4	51.6	51.8	52.0	52.1	52.4	52.5	52.8	52.8	53.0	53.3	53.4	53.7	53.9
.352	49.4	49.6	49.8	50.0	50.2	50.4	50.6	50.9	51.0	51.4	51.5	51.6	51.9	52.0	52.3	52.2	52.5	52.8	52.9	53.1	53.4
.354	48.8	49.0	49.3	49.5	49.6	49.8	50.0	50.3	50.5	50.7	51.0	51.0	51.4	51.5	51.7	51.7	52.0	52.4	52.5	52.6	52.8
.356	48.2	48.5	48.7	48.9	49.0	49.2	49.5	49.6	50.0	50.1	50.4	50.5	50.8	50.9	51.1	51.1	51.5	51.8	51.9	52.0	52.2
.358	47.6	47.8	48.0	48.3	48.4	48.6	48.9	49.1	49.4	49.5	49.8	49.9	50.3	50.3	50.5	50.5	51.0	51.3	51.3	51.5	51.6
.360	47.0	47.2	47.5	47.7	47.9	48.1	48.3	48.6	48.7	49.0	49.2	49.4	49.7	49.7	50.0	50.0	50.5	50.7	50.7	51.0	51.1
.362	46.5	46.7	47.0	47.1	47.4	47.5	47.7	48.0	48.1	48.4	48.6	48.9	49.0	49.1	49.5	49.5	50.0	50.1	50.2	50.4	50.6
.364	45.9	46.1	46.4	46.5	46.8	47.0	47.1	47.4	47.6	47.8	48.0	48.2	48.5	48.5	48.9	48.9	49.4	49.5	49.6	49.9	50.0
.366	45.2	45.5	45.7	46.0	46.2	46.4	46.5	46.9	47.0	47.2	47.5	47.6	48.0	48.0	48.4	48.3	48.7	49.0	49.1	49.4	49.5
.368	44.7	44.9	45.1	45.4	45.6	45.7	46.0	46.2	46.4	46.6	46.9	47.0	47.4	47.4	47.7	47.8	48.1	48.4	48.5	48.8	49.0
.370	44.1	44.3	44.5	44.8	45.0	45.1	45.5	45.6	45.9	46.0	46.3	46.5	46.8	46.9	47.1	47.2	47.6	47.8	48.0	48.2	48.4
.372	43.1	43.7	44.0	43.2	44.4	44.6	44.8	45.0	45.3	45.5	45.8	46.0	46.2	46.3	46.5	46.6	47.0	47.2	47.4	47.6	47.8
.374	42.8	43.1	43.4	43.6	43.8	44.0	44.2	44.5	44.7	44.9	45.1	45.4	45.6	45.7	46.0	46.1	46.4	46.6	46.8	47.0	47.2
.376	42.3	42.5	42.8	43.0	43.2	43.4	43.6	43.9	44.1	44.4	44.5	44.8	45.0	45.2	45.5	45.5	45.9	46.1	46.3	46.5	46.6
.378	41.6	41.9	42.1	42.4	42.6	42.8	43.0	43.3	43.5	43.8	44.0	44.1	44.5	44.5	44.9	45.0	45.3	45.5	45.7	45.9	46.0
.380	41.0	41.3	41.5	41.7	42.0	42.2	42.5	42.7	43.0	43.1	43.4	43.6	43.9	44.0	44.3	44.4	44.7	45.0	45.1	45.3	45.5
.382	40.6	40.7	40.9	41.1	41.4	41.6	41.9	41.0	42.4	42.5	42.8	43.0	43.3	43.4	43.6	43.8	44.1	44.6	44.7	44.8	45.0
.384	39.8	40.0	40.3	40.5	40.8	41.0	41.2	41.5	41.7	42.0	42.2	42.4	42.7	42.8	43.1	43.2	43.5	43.9	43.9	44.2	44.4
.386	39.1	39.4	39.7	39.9	40.2	40.4	40.6	40.8	41.1	41.4	41.5	41.8	42.1	42.2	42.5	42.6	43.0	43.2	43.3	43.6	43.8
.388	38.5	38.8	39.0	39.3	39.6	39.8	40.0	40.2	40.5	40.7	41.0	41.2	41.5	41.6	42.0	42.0	42.4	42.6	42.8	43.0	43.2
.390	37.9	38.1	38.4	38.6	38.9	39.2	39.4	39.6	39.9	40.0	40.4	40.5	40.8	41.0	41.4	41.4	41.8	42.0	42.2	42.4	42.6
.392	37.2	37.5	37.8	38.0	38.3	38.5	38.8	39.0	39.3	39.5	39.8	40.0	40.2	40.4	40.7	40.8	41.2	41.4	41.6	41.8	42.0
.394	36.6	36.8	37.2	37.4	37.7	37.8	38.2	38.4	38.7	38.9	39.2	39.4	39.7	39.8	40.1	40.2	40.6	40.8	41.0	41.2	41.4
.396	35.9	36.2	36.5	36.8	37.0	37.2	37.5	37.7	38.0	38.2	38.5	38.8	39.0	39.2	39.5	39.6	39.9	40.2	40.4	40.6	40.8
.398	35.3	35.6	35.9	36.1	36.4	36.6	36.8	37.1	37.4	37.6	37.9	38.2	38.4	38.6	38.9	39.0	39.4	39.6	39.8	40.0	40.2
.400	34.7	34.9	35.2	35.5	35.7	36.0	36.2	36.5	36.8	37.0	37.2	37.5	37.7	37.9	38.3	38.4	38.7	39.0	39.2	39.4	39.6
.402	34.0	34.3	34.6	34.8	35.1	35.3	35.6	35.9	36.2	36.4	36.6	36.9	37.2	37.4	37.7	37.8	38.1	38.4	38.6	38.8	39.0
.404	33.3	33.6	33.9	34.2	34.4	34.7	35.0	35.2	35.5	35.7	36.0	36.2	36.5	36.7	37.0	37.2	37.5	37.8	37.9	38.2	38.4
.406	32.6	33.0	33.2	33.5	33.8	34.0	34.3	34.6	34.8	35.1	35.4	35.6	35.9	36.0	36.4	36.5	36.9	37.1	37.3	37.6	37.8
.408	32.0	32.3	32.6	32.9	33.2	33.4	33.7	34.0	34.2	34.5	34.8	35.0	35.3	35.5	35.8	35.9	36.3	36.6	36.8	37.0	37.2
.410	31.4	31.6	32.0	32.3	32.5	32.7	33.0	33.3	33.6	33.8	34.2	34.4	34.6	34.8	35.2	35.2	35.7	35.9	36.1	36.4	36.6
.412	30.7	31.0	31.3	31.6	31.8	32.1	32.4	32.7	32.9	33.2	33.7	33.8	34.0	34.2	34.5	34.7	35.0	35.3	35.5	35.8	36.0
.414	30.0	30.4	30.6	30.9	31.2	31.4	31.7	32.0	32.3	32.5	32.8	33.1	33.3	33.6	33.8	34.0	34.4	34.7	34.9	35.2	35.4
.416	29.4	29.6	30.0	30.2	30.5	30.8	31.0	31.3	31.6	31.9	32.2	32.4	32.7	32.9	33.2	33.4	33.8	34.1	34.2	34.5	34.7
.418	28.6	29.0	29.3	29.6	29.9	30.1	30.4	30.7	31.0	31.2	31.6	31.8	32.0	32.3	32.6	32.8	33.1	33.4	33.6	33.9	34.1
.420	28.0	28.3	28.6	28.9	29.2	29.4	29.7	30.0	30.3	30.6	30.8	31.1	31.4	31.6	32.0	32.2	32.5	32.8	33.0	33.2	33.5
.422	27.3	27.6	27.9	28.2	28.5	28.7	29.0	29.3	29.6	29.9	30.2	30.4	30.7	30.9	31.3	31.4	31.8	32.1	32.3	32.6	32.8
.424	26.6	26.9	27.2	27.5	27.8	28.1	28.4	28.7	29.0	29.2	29.5	29.8	30.1	30.3	30.6	30.8	31.2	31.5	31.6	32.0	32.2
.426	25.9	26.2	26.6	26.8	27.2	27.4	27.7	28.0	28.3	28.6	28.9	29.2	29.4	29.6	30.0	30.2	30.6	30.8	31.0	31.3	31.6
.428	25.2	25.5	25.8	26.1	26.5	26.7	27.0	27.3	27.6	27.8	28.2	28.5	28.8	29.0	29.3	29.5	29.9	30.2	30.4	30.6	30.9
.430	24.5	24.8	25.2	25.4	25.8	26.0	26.3	26.6	26.9	27.2	27.5	27.8	28.1	28.3	28.7	28.9	29.2	29.5	29.7	30.0	30.3
.432	23.8	24.1	24.4	24.8	25.1	25.3	25.6	25.9	26.2	26.5	26.8	27.1	27.4	27.6	28.0	28.2	28.6	28.8	29.1	29.4	29.6
.434	23.1	23.4	23.8	24.1	24.4	24.6	24.9	25.3	25.6	25.9	26.2	26.5	26.8	27.0	27.4	27.5	27.9	28.2	28.4	28.7	29.0
.436	22.4	22.7	23.0	23.4	23.7	23.9	24.2	24.6	24.9	25.2	25.5	25.8	26.1	26.4	26.7	26.8	27.2	27.6	27.8	28.0	28.3
.438	21.6	22.0	22.3	22.7	23.0	23.2	23.6	23.8	24.2	24.5	24.8	25.1	25.4	25.6	26.0	26.2	26.5	26.8	27.1	27.4	27.7
.440	20.9	21.3	21.6	22.0	22.3	22.5	22.8	23.1	23.5	23.8	24.1	24.4	24.7	25.0	25.3	25.5	25.8	26.2	26.4	26.7	27.0
.442	20.3	20.6	20.9	21.3	21.6	21.8	22.2	22.5	22.8	23.1	23.6	23.8	24.0	24.3	24.6	24.9	25.2	25.5	25.8	26.1	26.3
.444	19.6	19.9	20.2	20.6	20.9	21.2	21.4	21.8	22.1	22.4	22.7	23.0	23.4	23.6	24.0	24.2	24.5	24.9	25.1	25.4	25.6
.446	18.8	19.2	19.5	19.8	20.2	20.4	20.8	21.1	21.4	21.7	22.0	22.3	22.7	22.9	23.2	23.6	23.8	24.2	24.4	24.7	25.0
.448	18.1	18.4	18.8	19.1	19.5	19.7	20.0	20.4	20.7	21.0	21.3	21.6	22.0	22.2	22.6	22.8	23.2	23.5	23.8	24.0	24.3
.450	17.4	17.7	18.0	18.4	18.7	19.0	19.3	19.7	20.0	20.3	20.6	21.0	21.3	21.6	21.9	22.1	22.5	22.8	23.1	23.4	23.6
.452	16.6	16.9	17.3	17.6	18.0	18.3	18.6	19.0	19.4	19.6	19.9	20.2	20.5	20.8	21.2	21.4	21.8	22.1	22.4	22.7	23.0
.454	15.9	16.2	16.6	16.9	17.2	17.6	17.9	18.2	18.6	18.8	19.2	19.5	19.9	20.1	20.4	20.7	21.0	21.4	21.6	22.0	22.2
.456	15.1	15.5	15.8	16.2	16.5	16.8	17.2	17.5	17.8	18.1	18.4	18.8	19.1	19.4	19.8	20.0	20.4	20.7	21.0	21.3	21.6
.458	14.4	14.7	15.1	15.4	15.8	16.1	16.4	16.9	17.1	17.4	17.7	18.1	18.4	18.7	19.0	19.3	19.7	20.0	20.3	20.6	20.9
.460	13.6	14.0	14.3	14.7	15.0	15.3	15.7	16.0	16.4	16.6	17.1	17.4	17.7	18.0	18.3	18.6	19.0	19.3	19.6	19.9	20.2
.462	12.9	13.2	13.6	13.9	14.3	14.6	15.0	15.3	15.6	16.0	16.3	16.6	17.0	17.3	17.5	17.9	18.3	18.6	18.9	19.2	19.5
.464	12.1	12.5	12.8	13.2	13.6	13.9	14.2	14.6	14.9	15.2	15.6	15.9	16.3	16.6	16.9	17.2	17.5	17.9	18.2	18.5	18.8
.466	11.4	11.8	12.1	12.5	12.8	13.1	13.5	13.8	14.2	14.5	14.8	15.2	15.5	15.8	16.2	16.5	16.8	17.2	17.5	17.8	18.1
.468	10.6	11.0	11.3	11.7	12.0	12.4	12.7	13.1	13.4	13.8	14.1	14.5	14.8	15.1	15.5	15.8	16.1	16.5	16.8	17.1	17.4
.470	9.9	10.2	10.6	10.9	11.3	11.7	12.0	12.4	12.7	13.1	13.4	13.7	14.1	14.4	14.7	15.1	15.4	15.7	16.0	16.4	16.6
.472	9.1	9.4	9.8	10.2	10.5	10.9	11.2	11.6	11.9	12.3	12.6	13.0	13.3	13.7	14.0	14.3	14.7	15.0	15.3	15.7	16.0
.474	8.3	8.7	9.0	9.4	9.8	10.1	10.5	10.9	11.2	11.6	11.9	12.3	12.6	13.0	13.3	13.6	14.0	14.3	14.6	15.0	15.3
.476	7.5	7.9	8.3	8.6	9.0	9.4	9.7	10.1	10.4	10.8	11.1	11.5	11.9	12.2	12.5	12.9	13.2	13.6	13.9	14.2	14.5
.478	6.7	7.1	7.5	7.9	8.3	8.6	9.0	9.3	9.7	10.0	10.4	10.8	11.2	11.5	11.8	12.2	12.5	12.9	13.2	13.5	13.8
.480	6.0	6.3	6.7	7.1	7.5	7.8	8.2	8.6	8.9	9.3	9.7	10.0	10.4	10.7	11.1	11.4	11.8	12.1	12.4	12.8	13.1
.482	5.2	5.6	5.9	6.3	6.7	7.1	7.4	7.8	8.2	8.5	8.9	9.3	9.6	10.1	10.4	10.7	11.0	11.4	11.7	12.1	12.4
.484	4.4	4.8	5.2	5.5	5.9	6.3	6.7	7.0	7.4	7.8	8.2	8.5	8.9	9.2	9.6	9.9	10.3	10.7	11.0	11.3	11.7
.486	3.6	4.0	4.4	4.8	5.1	5.5	5.9	6.3	6.6	7.0	7.4	7.7	8.1	8.5	8.9	9.2	9.5	9.9	10.2	10.6	10.9
.488	2.8	3.2	3.6	4.0	4.4	4.7	5.1	5.5	5.9	6.2	6.6	7.0	7.4	7.7	8.1	8.4	8.8	9.2	9.5	9.9	10.2
.490	2.0	2.4	2.8	3.2	3.6	4.0	4.3	4.7	5.1	5.5	5.8	6.2	6.6	7.0	7.4	7.7	8.0	8.4	8.8	9.1	9.4

INDEX

Abrams water-cement ratio law, 141
Accuracy of testing machines, 38, 45
Aggregate failure, 146
Aluminum, 6, 114, 116
American Society for Testing Materials, standards of, and organization, 26
Apparent elastic limit, Johnson's, 11
Application of stress-strain diagram, 5, 61-63, 117, 118
Area-Diameter Tables, 189-192
Area-Reduction Tables, 193-195
Autographic stress-strain recorders, 50, 52, 114

Beams
  deflection of, 82
  ductile and brittle materials, 186-188
  forces on, 77-81
  moment diagrams, 78
  shear diagrams, 78
  strain gage used with, 168
  stresses in, 79, 80
  testing, 83-85
  wood, 83, 179
Bending test, cold-bend, 74, 75
Bond failure in concrete, 146
Bond strength of plastics, 123
Brinell hardness tester, 127
Brittle and Ductile Materials in Flexure, Experiment 18, 186-188
Bronze, tension test of, 115
Buckling of columns, 150

Calibration of testing machine, 39-42
Capsule, hydraulic, 30, 36
Carbon
  Effect of Carbon Content on Properties of Steel, Experiment 3, 64-69
  pile strain gage, 161
  temper carbon, 109
Cement, 138
Cementite, 64
Ceramic products in flexure, 186
Charpy impact test, 98, 100
Checks, in beams, 82
Class organization in laboratory, 25
Cold-Bend, Tension, Compression, and Shear Tests of Metals, Experiment 4, 70-76
Column Tests, Experiment 13, 150-155
Companion bar method of calibrating testing machine, 40, 44
Compression, Shear, Cold-Bend, and Tension Tests of Metals, Experiment 4, 70-76
Compression, Shear, and Tension Tests of Wood, Experiment 15, 173-178
Compression test
  cast iron, 109
  concrete, 145
  plastics, 122
  spring, 182
  steel, 74
  wood, 175
Compressive strength, 2, 14
Compressometers, 145, 175
Computations, sample, 24
Concrete, the Physical Properties of, Experiment 12, 138-149
Concrete in flexure, 186
Concrete, structure of, 138
Consistency of concrete, 141, 144
Conversion chart for hardness, 134
Copper, tension test of, 115
Corrosion, 22
Creep, 20
Curves and diagrams, how to draw, 24

Data, tabulation of, 23
Defects in wood beams, 82
Deflection
  beams, 82
  springs, 182
Deflectometer, 85
Density of wood, 82

Diagrams and curves, how to draw, 24
Diameter-Area Tables, 189-192
Ductile and Brittle Materials in Flexure, Experiment 18, 186-188
Ductility, 15
Dynamometers, 42

Effect of Moisture upon the Flexural Properties of Wood, Experiment 16, 179-181
Elastic limit, proportional, 9
Elastic ratio, 19
Elastic resilience, modulus of, 17
Elasticity, modulus of, 7
Electrical strain gage, 159
Elongation, percentage, 15
Energy, determination of, in impact machine, 101
Energy, fracture, 67, 104
Energy lost, hysteresis, 19
Energy loads, 20
Energy, modulus of resilience, 18
Euler column formula, 151
Extensometer tension test, 53
Extensometer, types of, 49-53

Fatigue, 20
Firth hardness tester, 133
Flexural Properties of Wood as Effected by Moisture, Experiment 16, 179-181
Flexural Tests of Ductile and Brittle Materials, Experiment 18, 186-188
Flexual test of an I-beam using strain gages, 168
Flexual Test of a Wood Beam, Experiment 5, 77-87
Force slab, 35
Four-point test, 65
Fracture energy, 67, 104
Fractures, types of, 21, 22

Glass in flexure, 186-188
Grading of sand and gravel, 139
Grain, inclined in wood beams, 82
Grain size, relation to properties, 67
Gray, White, and Malleable Iron, Properties of, Experiment 8, 108-113
Graphite in iron, 108
Gravel, 139
Grips to hold specimens, 44, 56, 66

Hardness, 19, 125
Hardness, correlation with various types of testers and with tensile strength, 134, 135
Hardness Testing, Experiment 11, 125-137
Hardness testers
  Brinell, 127
  Rockwell, 129
  Shore Scleroscope, 132
  Vickers, 133
  Firth, 133
  Monotron, 133
Helical Spring, Test of, Experiment 17, 182-185
Horizontal shear in a beam, 79
Horizontal testing machine, 34
Hydraulic capsule, 30, 36
Hydraulic lever, in calibrating device, 40
Hydraulic testing machine, 29-31, 33-36
Hysteresis, 19

Impact loads, 20
Impact Tests of Ductile and Brittle Materials, Experiment 7, 98-107
Inductance strain gage, 161
Iron, Gray, White and Malleable, Properties of, Experiment 8, 108-113
Izod impact test, 98, 100

Jack, hydraulic
  with force slab, 35, 37
  with helical spring, 184
Johnson's apparent elastic limit, 11

Knife edges of testing machine, 29, 30
Knots in beams, 82

Levers of testing machine, 29, 30
Limit of elastic action, proportional elastic limit, 9
Load-elongation diagram, 114, 115
Loading system of testing machine, 29
Loading, types of, 20
Localized yielding, 55

Malleability, 15
Malleable Iron, Gray, and White, the Properties of, Experiment 8, 108-113
Mechanical lever testing machine, 29
Mechanical strain gage, 159
Metal working, 61-63, 117, 118
Modulus of
  elastic resilience, 17
  elasticity
    compression, 8
    shear, 9
    with strain gage, 168
    tension, 8
    secant, 145
    tangent, 11, 108
  resilience, 18
  rigidity, 9
  rupture, 81, 181, 187
Moisture and Its Effect upon the Flexural Properties of Wood, Experiment 16, 179-181
Moment diagrams for beams, 48
Monotron hardness tester, 133
Morehouse proving ring, 41

Neck at point of fracture, 56
Neutral axis in beam, 77, 79

Observer, duties, 25
Offset in yield strength, 13, 114
Operator, duties, 25
Optical strain gage, 162

Pearlite, 64
Photomicrographs of steel, 64
Plastics, the Physical Properties of Laminated Plastics, Experiment 10, 119-124
Plastics in flexure, 186
Poisson's ratio, 6
Portland cement, 138
Portland Cement Association, 140, 142, 147
Pound equivalent of testing machine, 30
Principal strain and stress, 163
Proportional elastic limit, 9
Proving levers, 40, 44
Proving ring, 41
Purpose of report, 23

Recorder, duties, 25
Reduction in area, percentage, 15
Reduction of Area Tables, 193-195
Reference to standards, 26
Repeated loads, 20
Reports, purpose of, 23
Resilience, modulus of elastic, 17
Resistance strain gage, 159
Rigidity, modulus of, 9
Rockwell hardness tester, 129
Rosette strain gage pattern, 164
Rupture, modulus of, 81

Sample computations, 24
Sand, 139
Scleroscope hardness tester, 132
Secant modulus of elasticity, 145
Sensitivity of testing machine, 38
Shakes, in beams, 82
Shear
  horizontal in a beam, 79
  strain, 4
  stress, 2, 3, 79, 182
  test, 71, 174
  vertical in a beam, 79
Shear, Cold-Bend, Tension, and Compression Tests of Metals, Experiment 4, 70-76
Shear, Tension, and Compression Tests of Wood, Experiment 15, 173-178
Shearing modulus of elasticity, 9
Shore Scleroscope hardness tester, 132
Significant figures, 26
Slenderness ratio, 151
Slump test, 144
Speed of testing, 39, 66
Spring, Test of a Helical Spring, Experiment 17, 182-185
Standards, reference to, 26
Static loads, 20
Strain
  compressive, 4
  gage data, interpretation of, 163
  gages, types
    electrical, 159
    mechanical, 159
    optical, 162
  principal, 163
  shear, 4
  tensile, 4
Strain Gages and Their Use, Experiment 14, 156-172

Strainometer, torsional, 91, 93
Stress
  compression, 2
  on oblique section, 3
  principal, 163
  shear, 2
  tension, 2
Stress-strain diagram
  application of, 5, 61-63, 117, 118
  Experiment 2, 48-63
  true, 7, 56, 59, 60, 104

Tabulation of data, 23
Tangent modulus, 11, 108
Temper carbon, 109
Temperature, correction for, in proving ring, 46
Tensile strength, 14
Tension bolts, 53, 56
Tension, Compression and Shear Tests of Wood, Experiment 15, 173-178
Tension, Compression, Shear, and Cold-Bend Tests of Metals, Experiment 4, 70-76
Tension test
  cast iron, 109
  malleable iron, 110
  non-ferrous metals, 114
  plastics, 122
  steel, 48, 66, 72
  wood, 173
  wrought iron, 72
Tension Test of Non-Ferrous Metals, Experiment 9, 114-118
Tension test with extensometer, 48, 109, 115
Test fractures, types of, 21, 22
Test of a Helical Spring, Experiment 17, 182-185
Testing machines
  accuracy, 38, 45
  calibration, 39, 42
  construction of, 28
  hardness, 127-133
  history, 27
  hydraulic, 29-31, 33-36
  impact, 98, 100
  loading system, 29
  mechanical lever, 29
  operation of, 43
  sensitivity, 38, 45
Testing machines
  Their Use and Calibration, Experiment 1, 27-47
  torsion, 91, 92
  types, 28, 29
  use, 27, 28
  weighing system, 29
Thermosetting, thermoplastic, plastics, 119
Troptometer, 91, 93
Torque on torsion specimen, 89
Torsion Tests of Ductile and Brittle Materials, Experiment 6, 88-97
Torsional strainometer, 91, 93
Toughness
  elastic, 17
  fracture, 16
True stress-strain diagram, 7, 56, 59, 60, 104
Twist of torsion specimen, 89

Ultimate strength, 14
Universal testing machine, 34

Vertical shear in a beam, 79
Vertical testing machine, 34
Vickers hardness tester, 133
Voids in cement, concrete, and concrete aggregates, 138

Water-cement ratio, 141
Water-cement ratio, table of values for various conditions of exposure, 149
Wear, 22
Weighing system of testing machine, 29
White Iron, Gray and Malleable, Properties of, Experiment 8, 108-113
Wissler dial, 84, 93
Wood in
  columns, 152
  compression, 175
  flexural properties, 77, 179
  moisture effects, 179
  shear, 174
  tension, 173
Working of metals, 61-63, 117, 118

Yield point, 11
Yield strength, 13
Young's Modulus, modulus of elasticity, 8

Zinc, tension test of, 115